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# **FUELS AND COMBUSTION HANDBOOK**



# FUELS AND COMBUSTION HANDBOOK

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## **FUELS AND COMBUSTION HANDBOOK**

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## PREFACE

Fuel is the backbone of all industrial prosperity; the use of heat and power, an index of a nation's degree of advancement. It is doubtful if there is any single material of supply more widely used by industries, or any general subject of any greater basic importance to engineers and industrialists.

Broad transitions in the use of fuel are inevitable as local supplies become depleted, improved combustion equipment is developed, and new demands are made upon fuel performance. Industries which formerly depended upon a single traditional fuel now find themselves choosing among two, three, or even four equally available fuels. The final choice is often dependent upon many factors, most of which involve the individual location and requirements of the plant.

Progress in combustion and in combustion equipment has banished an era in which "coal was just coal" and brought us to a point where the specification of a properly coordinated fuel can, and frequently does, result in savings of thousands upon thousands of dollars.

A better understanding of the characteristic properties of the individual fuels, and of the several fuels as related to each other, paves the way for a more intelligent fuel selection and for the resultant substantial economies and improvements in operation.

Despite a wealth of up-to-date material on fuels of all types, no recent attempt has been made to bring representative factual material together for ready reference. Such authoritative data as were available to cover many important phases of fuel characteristics and utilizations existed only in pamphlet or article form, scattered throughout engineering societies, government bureaus, and trade journals.

It was thus the objective of this volume to present comprehensive factual data over the full range of commercial fuels for reference and study by practical engineers, students of fuels, and all others having an interest in the selection or use of fuels or fuel utilization equipment of any type.

To be of any real value, a handbook of this type must necessarily be comprehensive in its coverage. As this requirement placed it well beyond the range of any single author, the volume was in effect compiled from some four hundred and fifty major references with the permission and cooperation of their authors and copyright owners. In selecting this wide range of material, every effort was made to use the most recent articles available with, of course, full consideration for their weight and value. As a result, over 50 per cent of the material presented herein is less than 5 years old, and over 80 per cent is less than 10 years old. It is fully realized that this may lead to conflict with older references and opinions in some instances. However, as only well-authenticated and carefully selected references were cited, the version presented may be assumed to be that in current acceptance.

As it is fully appreciated that no reference book is any better than its index, every effort has been made to make this as complete as possible. In arranging the material, a major complication was that much of the material had two or even more very logical locations. In such instances, after making the best choice possible, included subjects were so indexed and cross-indexed as to make them readily available.

Cooperation in the preparation of this book was so wholehearted and widespread as to render a full acknowledgment of all participants a major problem. First, the

work of the editors was, just as the term implies, largely that of collecting, arranging, and presenting material from a broad field with but little claim to original authorship. Next, individual credit has been given in the text for each reference used. The amount of rewriting differed widely from article to article but, as virtually all the material was rewritten or rearranged, if only to a slight extent, direct quotations were omitted for the sake of simplification in reading. Finally, the editor wishes to express sincere thanks to all whose cooperation is not otherwise covered, including: Dr. A. C. Fieldner, Chief, Fuels and Explosives Division, U.S. Bureau of Mines; J. F. Barkley, Chief, Fuels Utilization Branch, U.S. Bureau of Mines; V. F. Parry, Supervising Engineer, U.S. Bureau of Mines; Joseph A. Corgan, Chief, Anthracite and Coke Section, U.S. Bureau of Mines; L. L. Newman, Gas Engineer, U.S. Bureau of Mines; T. W. Harris, Division Purchasing Agent and W. H. Gehring, Assistant Division Purchasing Agent, E. I. duPont de Nemours & Co.; J. Stanley Morehouse, Dean of Engineering, Villanova College; Dr. E. Hacisch, Head of Chemistry Department, Wabash College; E. Church, Jr., Professor, Polytechnic Institute of Brooklyn; Dr. A. W. Gauger, Director, Mineral Industries Experiment Station, The Pennsylvania State College; A. C. Christie, Professor, Johns Hopkins University; Otto deLorenzi, Director of Education, Combustion Engineering-Superheater, Inc.; Paul A. Mulcey, Director, Anthracite Institute Laboratory; J. H. Kerriek, Fuel Engineer, Philadelphia & Reading Coal Iron Co.; E. E. Finn, Consulting Engineer, Anthracite Institute; C. M. McHeffey, Fuel Engineer, Hudson Coal Co.; E. C. Lindenmoyer, Sales Engineer, M. A. Hann Co.; T. C. Thomas, Captain, U.S. Navy; A. W. Thorson and W. A. Lurtey, United Engineers and Constructors; W. H. Jackson, Babcock & Wilcox Co.; Robert Hunge, Buffalo Forge Co.; W. L. Byler, Mackenzie Engineering Co.; B. W. Webb, Combustion Engineering-Superheater, Inc.

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*September, 1950*

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## LIST OF ABBREVIATIONS

AGA	American Gas Association
AIME	American Institute of Mining and Metallurgical Engineers
amp	amperes
API	American Petroleum Institute
ASHVE	American Society of Heating and Ventilating Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
atm	atmospheres
bbl	barrels
bhp	brake horsepower
Btu	British thermal units
cal	calories
cc	cubic centimeters
cfm	cubic feet per minute
chu	centigrade heat units
cm	centimeters
cu ft	cubic feet
db	decibels
deg	degrees
°C	degrees centigrade
°F	degrees Fahrenheit
E.D.R.	equivalent direct radiation
fpm	feet per minute
fps	feet per second
ft	feet
ft-lb	foot-pounds
g	grams
g-cal	gram-calories
gph	gallons per hour
gpm	gallons per minute
hp	horsepower
hp-hr	horsepower-hours
hr	hours
ICC	Interstate Commerce Commission
ID	inner diameter
in.	inches
in. Hg	inches of mercury
I.P.S.	iron pipe size
IT	international
kB	thousand Btu
kc	kilocycles
kcal	kilocalories
kg	kilograms
km	kilometers
kva	kilovolt-amperes
kw	kilowatts
kwhr	kilowatthours
l	liters
lb	pounds
LPG	liquefied petroleum gas
m	meters
Mcf	thousand cubic feet
mg	milligrams
min	minutes
MIT	Massachusetts Institute of Technology

ml	milliliters
mm	millimeters
mm Hg	millimeters of mercury
mph	miles per hour
NBS	National Bureau of Standards
NGAA	National Gas Association of America
OD	outer diameter
oz	ounces
ppm	parts per million
psf	pounds per square foot
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gravity
R.O.M.	run of mine
rpm	revolutions per minute
SAE	Society of Automotive Engineers
sec	seconds
sq ft	square feet
whr	watthours

# **SECTION 1**

## **SOLID FUELS**



## CHAPTER 1

---

### FUEL SOURCES, TRENDS, AND RESERVES IN THE UNITED STATES AND ABROAD

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## SOURCES OF ENERGY<sup>1</sup>

During the period 1912 to 1947, the steady rise in mechanization pushed the world's consumption of total energy derived from all fuels and water power up almost 70 per cent to a 1947 total of more than 79 quadrillion (79,000,000,000,000,000) Btu.<sup>2</sup>

The United States, with its many machines and wide acceptance of both labor-saving devices and comfort living, is by far the world's greatest user of energy. In 1947, this country accounted for 45 per cent of total world consumption; Russia, the second largest consumer of energy, was credited with only 11 per cent.

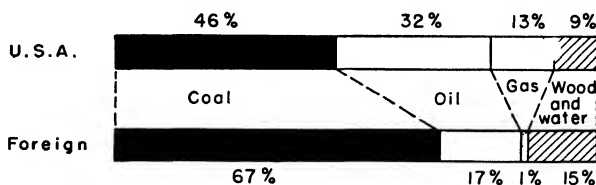


FIG. 1-1. Estimated proportions of energy supplied in 1947. (*The Lamp*, June-September, 1948.)

Upon a per capita basis, the United States looms even larger among world energy consumers. Every man, woman, and child uses, on the average, about 250 million Btu each year; in Canada, which ranks second in the per capita comparison, each person uses about 210 million Btu.

In Asia, Oceania, and most of Africa, the average person uses only about 6 million Btu, less than one-fortieth as much energy as the average American uses. Even though 60 per cent of the world's people live in those areas, they consume only 10 per cent of the world's energy.

## GENERAL TRENDS IN THE USE OF ENERGY

Until the end of the nineteenth century, the world depended almost entirely upon wood, coal, and water power for its industrial energy. Oil entered the energy picture early in the twentieth century with the development of the gasoline-burning internal-combustion engine. Gasoline's high energy content, cleanliness, and ease of handling and storing made it an ideal fuel for moving vehicles; and its use soon spread from automobiles to trucks and busses, to farm tractors, boats, and airplanes. In even more recent times, other types of fuel derived from petroleum have been used increasingly to power oil-fired boilers and steam locomotives, and diesel engines for driving locomotives, trucks, and busses. As oil has also become a major supplier of such other energy needs as space heating, the result was a fivefold expansion of the use of oil and gas between the years 1920 and 1947.

In 1947, for the first time, coal and oil were virtually tied as producers of energy in the United States, with each supplying approximately 48 per cent of all energy consumed.<sup>3</sup> However, even if it has not already reached its peak, this trend cannot continue indefinitely because our petroleum reserves are by no means as extensive as our coal reserves and because the demand for oil is increasing at a rate that is likely to be

<sup>1</sup> ANONYMOUS, *Energy*, *The Lamp*, Esso Standard Oil Co., New York, June-September, 1948. SILLCOX, K. L., "Patterns of Power," presented at the Massachusetts Institute of Technology, Mar. 17, 1948.

<sup>2</sup> A Btu (British thermal unit), the common standard for measuring energy in fuels, is defined as the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit.

<sup>3</sup> Exclusive of wood.

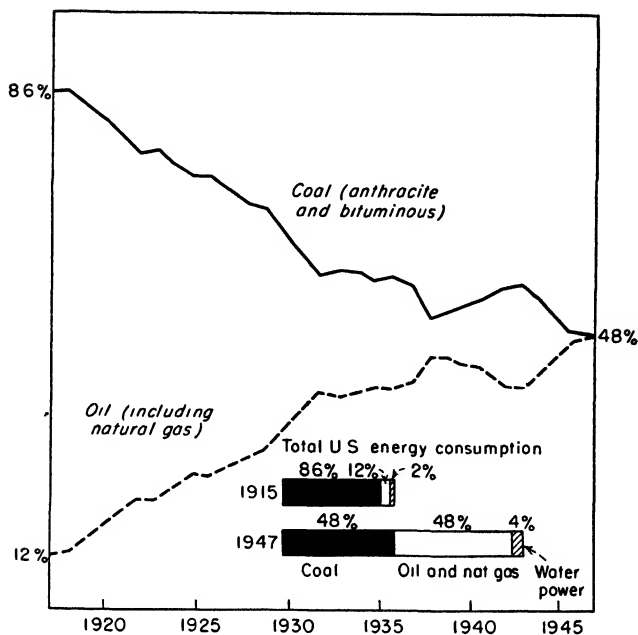


FIG. 1-2. Percentages of United States energy supplied by coal and oil (including natural gas), 1917 to 1947. (*The Lamp*, June-September, 1948.)

greater than the rate of increase that can be maintained in domestic production. (This is due principally to the limitations on the rate at which oil fields can be developed without drawing upon our oil resources at such an inefficiently high rate as to be wasteful.)

Table 1-1. Per Capita Consumption of Energy by Countries\*

Country	Energy produced per day, per capita, kwhr	Total energy produced by coal, per cent	Country	Energy produced per day, per capita, kwhr	Total energy produced by coal, per cent
United States	10 02	61 00	Japan	1 27	47 20
Canada	10 00	40 70	Argentina.	1 27	24 30
Norway	5 75	17 50	Italy	1 26	33 50
Great Britain	5 00	86 00	Spain	1 05	42 80
Germany	4 95	88 90	Russia	0 71	37 90
Sweden	3 36	27 10	Brazil	0 47	13 40
Switzerland	3 37	22 10	India	0 36	22 80
France	3 25	71 75	China.	0 34	23 80
Australia	2.80	45 40			

\* U.S. Bureau of Mines, 1949.

The already small deficit between the efficient domestic producing rate and domestic demand is expected to grow. This difference is already being made up by imports, and it seems likely that foreign crude will continue to support our domestic production, probably to a steadily increasing degree.

At present, most of our imports come, and are expected to continue to come, from the Western Hemisphere, particularly Venezuela. In past years, the highly industrialized areas of western Europe, too, have drawn much of their oil from Venezuela, as well as from the United States.

Today, however, the pattern of oil flow is changing. With the demand for oil rising in practically all of the North and South American countries, petroleum sources in this hemisphere are being looked to increasingly to supply these needs. Other sources, therefore, are being developed to meet the needs of consumers in western Europe. By far the most important of these sources of supply for the Eastern Hemisphere is the Middle East. There proved reserves are already greater than those of the United States, and potential or final reserves are far greater.

Table 1-2. End Uses of United States Energy in 1947<sup>1</sup>

Use	Btu (trillions)	Per cent	Use	Btu (trillions)	Per cent
Industrial (manufacturing) and miscellaneous . . . .	14,000	39.5	Highway vehicles.....	3,600	10.1
Space heating. . . . .	8,500	23.9	Ships . . . . .	700	2.0
Gas and electricity production . . . . .	4,800	13.5	Aviation (commercial and military).....	100	0.3
Railroads.....	3,800	10.7	Total . . . . .	35,500	100.0

<sup>1</sup> Energy, *The Lamp*, Esso Standard Oil Co., New York, June-September, 1948.

Table 1-3. Sources of Commercial Energy Supply in the United States for 1946<sup>1</sup>  
(Excluding manual labor)

Source	Energy equivalent		
	Trillions of Btu	Per cent of total energy	Per cent of major energy sources
Coal.....	15,589	46.08	47.87
Crude petroleum.....	10,401	30.75	31.94
Natural gas <sup>a</sup> .....	5,199	15.37	15.97
Hydroelectric power <sup>b</sup> .....	1,374	4.06	4.22
Total major sources . . .	32,563	96.26	100.00
Wood and agricultural products . . .	1,124	3.32	
Work animals . . . . .	122	0.36	
Mechanical water power.....	10	0.03	
Wind . . . . .	10	0.03	
Total commercial energy. . . . .	33,829	100.00	

<sup>1</sup> Interfuel Competition, *Federal Power Commission Report on the Natural Gas Investigation*, Part VII, p. 20, February, 1948.

<sup>a</sup> Does not include growing usage of "natural-gas liquids."

<sup>b</sup> At prevailing central-station fuel equivalent.

Table 1-4. Annual Work Output of Men and Animals<sup>1</sup>

Horse } .....	800 hr/year @ 1 hp	600 kwhr/year
Buffalo } .....		
Camel } .....		
Ox.....	800 hr/year @ 11/12 hp	550 kwhr/year
Mule.....	800 hr/year @ 3/4 hp	450 kwhr/year
Ass.....	800 hr/year @ 1/4 hp	150 kwhr/year
Man.....	2,400 hr/year @ 1/12 hp	150 kwhr/year

<sup>1</sup> Energy Resources of the World, *U.S. Dept. State Pub. 3428*, June, 1949, p. 124, Washington, D.C.

**Oil Trends in the United States.** No factor in the entire fuel picture is any more uncertain than that of the future of the oil industry as we know it today. From a maze of conflicting opinions, it can be concluded, because of a preponderant weight of evidence, that (1) our coal reserves are abundant for at least several hundred years, (2) within the next 5 or 10 years it will be economically feasible to transform coal into gaseous and liquid forms, and (3) our domestic natural oil reserves are definitely limited.

Proved oil reserves in the United States stand at  $21\frac{1}{2}$  billion bbl, the largest in our history. However, this figure is offset by equally record consumption and by growth of consumption to a point where a simple division of proved reserves by the annual

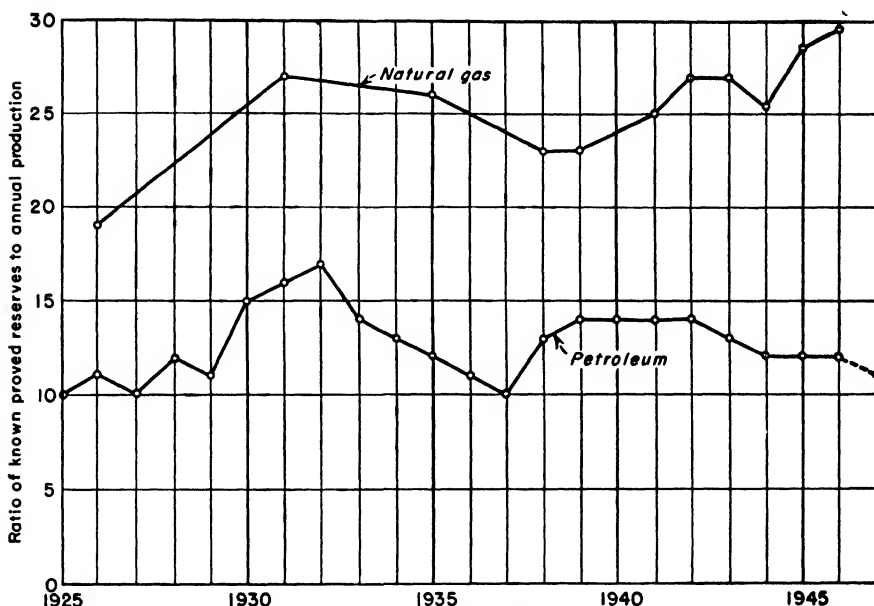


FIG. 1-3. Ratio of proved recoverable natural-gas and petroleum reserves to annual production. (Compiled from Table 3 in "Natural Gas Investigation," Part VII, *Interfuel Competition*, Federal Power Commission, Docket G580, February, 1948.)

rate of even present use of 2 billion bbl indicates a life for our reserves of less than 12 years. (However, it is interesting to note in Fig. 1-3 that this figure has not exceeded 14 years since 1932.)

Fortunately, there are several major fallacies in this type of reasoning. First, proved reserves represent only the known working stocks of underground oil, against the certainly larger, but unknown, total or potential ultimate supply. New discoveries and improvements in recovery are always adding to our proved reserves, yet there is no really accurate measure of their true magnitude. The recent Leduc discovery in western Canada, the offshore potentialities of the Gulf Coast, and the tremendous increase in both United States and Venezuelan production over what was previously believed a maximum, together with advances in methods of secondary recovery, all indicate the potentialities of an expansion of domestic oil through unpredictable factors.

Secondly, increased demand for such oil-consuming machines as diesels, automobiles, and oil burners cannot properly reflect a corresponding demand for oil unless

future equipment, efficiencies, and a consideration of the fuels displaced are included in the calculation. For illustration, the use of diesel locomotives is frequently criticized as a consumer of our limited oil supply. Actually this criticism is unwarranted, particularly in the West, because, wherever a diesel replaces one of the many oil-burning steam locomotives, it does so at so much higher fuel efficiency that oil is actually saved. In fact, it is estimated that, if 80 per cent of all locomotives now in use in this country were diesels, the total railroad energy of the country would be cut by at

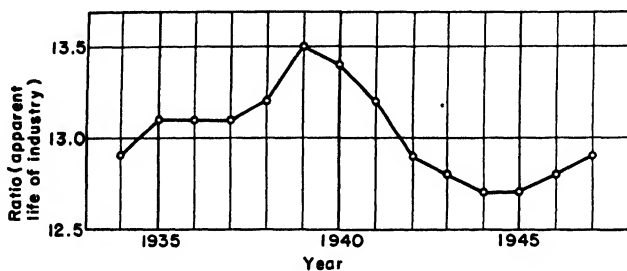


FIG. 1-4. Ten-year moving ratio between recoverable petroleum reserves and annual production. (Note: Each point on curve represents average of current year and nine preceding years, i.e., a moving average to show the trend.)

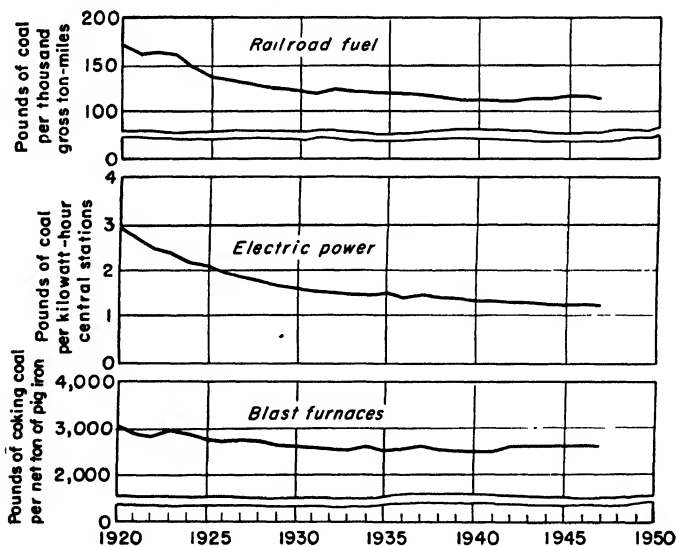


FIG. 1-5. Trends in fuel efficiency in the United States, 1920 to 1947. (U.S. Bureau of Mines, *Mineral Market Report* 1664.)

least 50 per cent because of the diesel's 4:1 efficiency ratio as compared with either coal- or oil-burning steam locomotives. On that basis, our railroads would then require less than half of the 11 per cent of the nation's total energy which they are now consuming.

Further economy is to be expected on the highways as a result of greater automotive efficiencies. Today, the fuel economy of automobiles is some 33 per cent greater than that of 30 years ago with a further 30 per cent economy, or 5 more miles per gallon, predicted for the foreseeable future.

All other classes of energy utilization, including space heating and industrial power, are also likely to yield to engineers' and researchers' constant search for greater economy.

Changing price relationships can also conceivably act as an effective brake upon the utilization of petroleum products. This is particularly true in the industrial field where even slight changes in the economic structure, such as would inevitably accompany any shift in petroleum supply, can cause appreciable conversions. In home heating, the price differential must be substantially greater to induce householders to make any sacrifices in convenience. However, technical developments in coal utilization are not expected to remain static; new types of equipment for the more automatic handling of coal and ash, together with greater efficiency of burning, could bring a major change back to solid fuels to relieve further the load upon oil.

As a net result, such improvements in utilization may slow down the increase in oil demand to extend the life of our proved reserves proportionately even in the face of a very desirable unrestricted expansion of the use of energy. All such factors will add

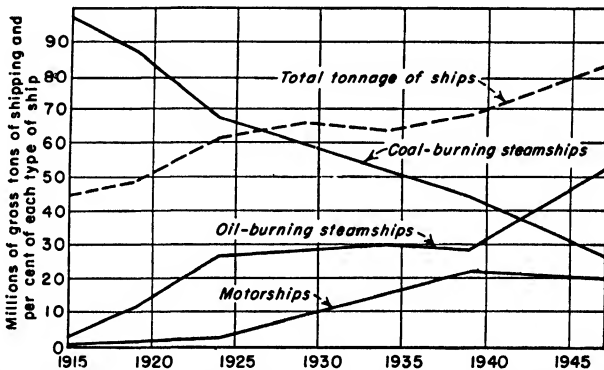


FIG. 1-6. World trend in steamship fuels, 1914 to 1947. (*The Lamp*, January, 1949.)

their share to a delay in the date when the United States must place major dependence upon foreign petroleum supplies. Even then, an alternate to guarantee us against any really fundamental change in our use of energy is the liquefaction of coal, oil shale, and natural gas.

**Solid-fuel Trends in the United States.** By far the greatest potential energy resource of this nation is in the form of coal. Again it becomes impossible to predict accurately the life of our reserves because of the absolutely unpredictable demands of the far distant years. However, even after a full allowance of all conservative factors, including coal's assumption of all the present energy production of oil, there is still enough coal for several hundred years. Nor does this fuel supply necessarily have to be used in solid form, since, when economic conditions justify it, liquid fuels can be derived from coal, and possibly additional and almost inexhaustible tonnages of oil shale, by technical processes already largely developed.

Within the life of any of our present plants, or possibly even methods of use, the limitation on coal is one of types and kinds, rather than one of total supply. Because of our natural practice of mining the best and most sought coal first, a distinct shortage of some of the higher grades of coal is already being experienced. As mining progresses, industry can expect steady, though gradual, lessening of a choice of coal characteristics; this should at least be balanced by improvements in utilization to nullify any over-all effects.

**Natural-gas Trends in the United States.** Despite distributional limitations, natural gas provided more than 13 per cent of the nation's energy supply in 1947. As much of our natural gas is a by-product of the search for, and production of, oil, its trend may be expected to parallel that of petroleum with one important exception.

Table 1-5. World Fuels Production in 1946<sup>1</sup>

Country	Coal		Petroleum		Natural gas
	Millions of metric tons <sup>a</sup>	Per cent of total	Millions of bbl	Per cent of total	Billions of cu ft
North America . . . . .	556 <sup>b</sup>	42.4	1,791	65.1	4,954
United States . . . . .	539	41.1	1,733	63.0	4,904
Canada . . . . .	16	1.2	8	0.3	48
Mexico . . . . .	1	0.1	49	1.8	2
South America . . . . .	3	0.2	466	17.0	.
Venezuela . . . . .	.....	...	389	14.1	.
Columbia . . . . .	.....	...	22	0.8	.
Argentina . . . . .	.....	...	21	0.8	.
Trinidad and Barbados . . . . .	.....	...	20	0.7	.
Peru . . . . .	.....	...	13	0.5	.
Chile . . . . .	2	0.1			
Brazil . . . . .	1	0.1			
Europe . . . . .	645 <sup>c</sup>	49.1	219	8.0	
Germany . . . . .	114	8.7	5	0.2	
Great Britain . . . . .	179	13.6			
U.S.S.R. . . . .	160	12.2	170 <sup>d</sup>	6.2	
France . . . . .	50	3.8			
Poland . . . . .	48	3.7	1		
Czechoslovakia . . . . .	34	2.6			
Belgium . . . . .	23	1.8			
Asia . . . . .	60	4.6	265	9.6	
Japan . . . . .	25	1.9	1		
U.S.S.R. . . . .	*	*			
India, Burma, Malaya . . . . .	30	2.3	3	0.1	
Iran, Iraq, Arabia . . . . .	.		256	9.3	
China, Manchuria . . . . .	*		1		
East Indies . . . . .	...	...	4	1	
Africa . . . . .	26	2.0	9	0.3	
Egypt . . . . .	.		9	0.3	
Union of South Africa . . . . .	24	1.8			
Australia and New Zealand . . . . .	22 <sup>e</sup>	1.7			
Australia . . . . .	20	1.5			
World totals . . . . .	1,312 <sup>f</sup>	100.0	2,750	100.0	4,954

<sup>1</sup> Prepared by Dr. Arno C. Fieldner, Chief, Fuels and Explosives Division, U.S. Bureau of Mines, January, 1948.

<sup>a</sup> A metric ton = 2,204.6 lb.

<sup>b</sup> Includes 5 million metric tons of subbituminous coal and lignite.

<sup>c</sup> Includes 97 to 122 million metric tons of lignite and brown coal.

<sup>d</sup> Includes Asia.

<sup>e</sup> Includes 7 million metric tons of lignite and brown coal.

<sup>f</sup> Countries not reported may raise total to 1,380 million metric tons. Includes approximately 125 million metric tons of lignite and brown coal.

\* Data not available.

This is that today much of our readily available natural gas is not being profitably marketed because of pipe-line limitations. Current plans call for relief to a point where we may expect a rapid and very substantial increase within a relatively short while. Like coal, the life of the gas fields is inseparably dependent upon the increase in demand, and upon the extent to which natural gas is called upon to bolster oil sup-

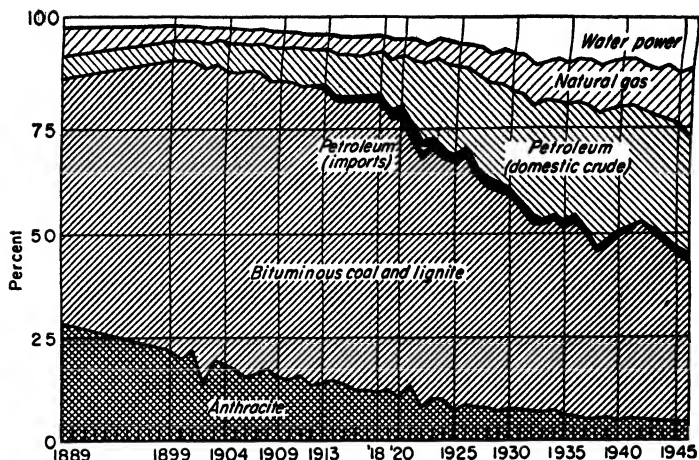


FIG. 1-7. Percentage of total Btu equivalent contributed by the several sources of energy in the United States, counting water power at constant fuel equivalent, 1889 to 1943. If water power is counted at the prevailing fuel equivalent of central stations in each year, its proportion is 3.2 per cent in 1889 and 4.2 per cent in 1943, and the proportions of the other sources of energy are affected accordingly. (*"Minerals Yearbook," U.S. Bureau of Mines, 1946.*)

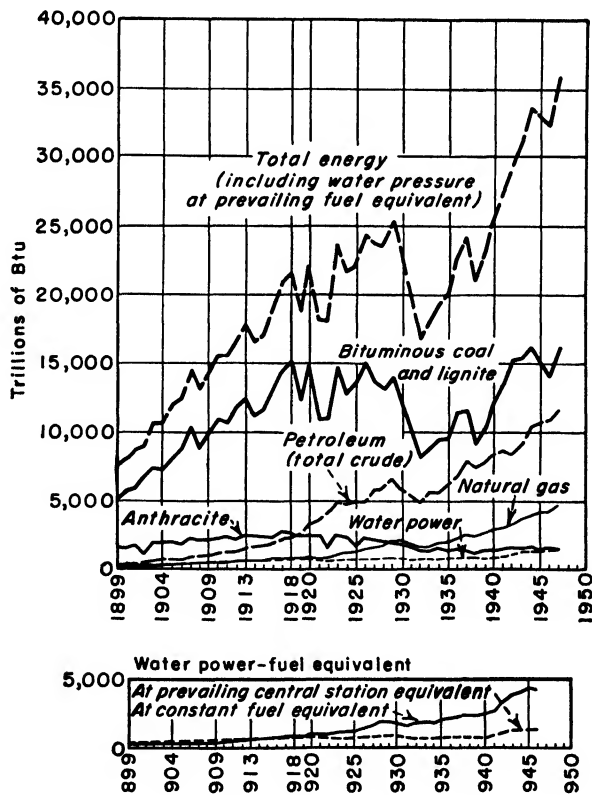


FIG. 1-8. Annual supply of energy from mineral fuels and water power in the United States, 1899 to 1947. (*U.S. Bureau of Mines, Mineral Market Report 1664.*)



plies either in direct use or in synthesis. Current estimates place the life of proved reserves at about twice those of oil which, of course, is still only a small fraction of that of coal.

**Possible New Energy Sources.** The foregoing considers only energy sources with which we are familiar today. But other sources, as yet untapped, are potential future suppliers. Included are nuclear fission, a utilization of the energy of sunlight, or the latent heat energy in the atmosphere, the earth, or ocean currents. Of these, atomic energy offers the greatest promise, with authorities agreeing that this will come gradually, possibly starting in stationary power plants and large ships.

Our present unspectacular problem is one of unceasing efforts to increase efficiencies so as to secure more energy from less fuel, and so to develop and distribute our energy resources as to hold waste and avoidable losses to a minimum.

## WORLD MINERAL-FUEL RESERVES

### World Coal Reserves<sup>1</sup>

The world's reserves of all types of coal ranging from lignite through anthracite have been estimated at 6 to 7 million metric tons. Of this amount, approximately 69 per cent occurs in North America, over 17 per cent in Asia, about 11 per cent in Europe, 2 per cent in Oceania, and the remaining 1 per cent in Africa and South America.

Very few countries are wholly devoid of coal. But many, such as Brazil, Argentina, Italy, Sweden, and Rumania, possess somewhat meager resources in proportion to their commercial and economic significance and consequently are dependent upon its importation to fill their requirements adequately. Norway's coal resources, irrespective of Spitzbergen, are inconsiderable.

**Bulk of Coal Reserves in Northern Hemisphere.** The great bulk of the coal reserves of the world occurs in the Northern Hemisphere. This is mainly due to the larger land areas existing there and to the fact that the earlier coal-bearing portions of the Carboniferous Era are not represented in the Southern Hemisphere. Another salient feature is the enormous coal resources of North America, which contain more than five-sevenths of the estimated reserves of the world, followed by those of Asia, which comprise the largest anthracite areas, occurring chiefly in China. Although it is probable that a large portion of China's coal, now classed as anthracite, may prove to be subbituminous coal, nevertheless that nation's resources in anthracite far exceed those of all other countries combined.

### Notes on Coal Occurrence and Types as Found in Various Countries

(See Table 1-6)

**North America** has 69 per cent of the world's coal reserves.

*Alaska* has reserves of 100 billion net tons (1946 estimate). Production in 1943, 289,230 net tons; 1943 consumption, 333,850 net tons. Most important fields: Matanuska Valley field, Cook Inlet region, and Nemana field in Yukon region. All types of coal found, from anthracite through lignite.

*Canada* has about 17 per cent of the world's reserves of all classes of coal. Lignite through good steaming and coking coals with some small deposits of anthracite. Coal in British Columbia mainly bituminous; Alberta, bituminous coal and lignite; Saskatchewan, lignites only; good steaming and coking coal on the Atlantic Coast.

*Mexico.* Considerable deposits are known, with relatively little exploration or development on account of the abundance of oil. State of Coahuila contains only highly developed fields; Sabinas Basin, 15 by 35 miles in area, most important with

<sup>1</sup> HOAR, H. M., "The Coal Industry of the World," U.S. Department of Commerce, Trade Promotion Series, No. 105, Government Printing Office, Washington, D.C., 1930.

**Table 1-6. Estimated Coal Reserves of the World**  
(In million metric tons of 2,204.6 lb each)

Country	1913 estimate and breakdown <sup>a</sup>				Jan., 1947, estimate <sup>b</sup>
	Class A, anthracite and semi- anthracite	Classes B and C, bituminous coals	Class D, subbitumi- nous coal, brown coal, and lignite	Total	Total
<b>North America<sup>c</sup>.....</b>	<b>21,842</b>	<b>2,239,683</b>	<b>2,811,906</b>	<b>5,073,431</b>	<b>3,707,000</b>
United States . . . . .	19,684	1,955,521	1,863,452	3,838,657	2,885,000 <sup>d</sup>
Canada . . . . .	2,158	283,661	948,450	1,234,269	815,000 <sup>e</sup>
Newfoundland . . . .		500		500	
Central America . . .		1	4	5	
<b>South America<sup>f</sup> . . .</b>	<b>700</b>	<b>31,397</b>	<b></b>	<b>32,097</b>	<b>3,000</b>
Colombia . . . . .		27,000		27,000	
Venezuela . . . . .		5		5	
Peru . . . . .	700	1,339		2,039	
Argentina . . . . .		5		5	
Chile . . . . .		3,048		3,048	2,000
<b>Europe<sup>g</sup>.....</b>	<b>54,346</b>	<b>693,162</b>	<b>36,682</b>	<b>784,190</b>	<b>882,000<sup>h</sup></b>
Great Britain and Ire	11,357	178,176		189,533	174,000
Portugal . . . . .	20			20	
Spain . . . . .	1,635	6,366	767	8,768	
France . . . . .	3,271	12,680	16,032	17,583	9,000
Italy . . . . .	144		99	243	
Greece . . . . .			40	40	
Bulgaria . . . . .		30	358	388	
Denmark . . . . .			50	50	
Netherlands . . . . .	320	4,082		4,402	
Belgium . . . . .		11,000		11,000	11,000
Germany . . . . .		409,975	13,381	423,356	342,000
Poland . . . . .					96,000
Czechoslovakia . . . .					19,000
Austria . . . . .		40,982	12,894	53,876	
Bosnia (Yugoslavia)			3,676	3,676	
Servia (Yugoslavia)		45	484	529	
Rumania . . . . .			39	39	
Sweden . . . . .		114		114	
Russia in Europe	37,599	20,849	1,658	60,106	80,000 <sup>i</sup>
Spitzbergen . . . . .		8,750		8,750	
<b>Asia . . . . .</b>	<b>407,637</b>	<b>760,098</b>	<b>111,881</b>	<b>1,279,586</b>	<b>1,455,000</b>
Korea . . . . .	40	19	22	81	
China . . . . .	387,464	607,523	600	995,587	250,000
Manchuria . . . . .	68	1,140		1,208	
Japan . . . . .	62	7,130	778	7,970	16,000
Russia in Asia . . . .	1	66,034	107,844	173,879	1,160,000
Indo-China . . . . .	20,002			20,002	
India . . . . .		76,399	2,602	79,001	
India, Burma, Malaya					20,000
Persia . . . . .		1,858		1,858	
<b>Africa . . . . .</b>	<b>11,662</b>	<b>45,123</b>	<b>1,054</b>	<b>57,839</b>	<b>212,000</b>
Belgian Congo . . . . .		90	900	990	
Southern Nigeria . . . .			80	80	
Rhodesia . . . . .	2	592	74	669	
Transvaal . . . . .		36,000		36,000	
Natal . . . . .	4,700	4,600		9,300	
Zusuland . . . . .	6,000			6,000	
Orange Free State . . . .	960	3,800		4,760	
Union of South Africa . .					206,000

Table 1-6. Estimated Coal Reserves of the World. (Continued)

Country	1913 estimate and breakdown <sup>a</sup>				Jan., 1947, estimate <sup>b</sup>
	Class A, anthracite and semi-anthracite	Classes B and C bituminous coals	Class D, subbituminous coal, brown coal, and lignite	Total	Total
Oceania.....	659	133,481	36,270	170,410	59,000
Australia.....	659	132,250	32,663	165,572	58,000
New Zealand.....		911	2,475	3,386	
British North Borneo.....		75	...	75	
Netherlands Indies.....		240	1,071	1,311	
Philippines.....		5	61	66	
World Total.....	498,846	3,902,944	2,977,763	7,397,553	6,318,000

<sup>a</sup> HOAR, H. M., "The Coal Industry of the World," U.S. Department of Commerce, Trade Promotion Series, No. 105, p. 13, Government Printing Office, Washington, D C., 1930.

<sup>b</sup> Letter and table from Dr. A. C. Fieldner, Chief, Fuels and Explosives Division, U.S. Bureau of Mines, 1947. Political names are as of the time of the reconnaissance.

<sup>c</sup> Mexico has considerable reserves of coal, but estimates are unavailable. Lignite in worth-while quantities has been found in Greenland, Labrador, Costa Rica, Panama, Trinidad, and the Dominican Republic.

<sup>d</sup> Includes 854 billion tons lignite and 744 tons subbituminous coal.

<sup>e</sup> Includes 573 billion tons lignite and subbituminous coal.

<sup>f</sup> Unestimated coal is in Bolivia, Ecuador, Uruguay, and Brazil.

<sup>g</sup> Meager reserves are found in Switzerland, Denmark, Iceland, Norway, Montenegro, and Turkey.

<sup>h</sup> Includes 111 billion metric tons lignite and brown coal.

<sup>i</sup> More recent estimates place Russia in Europe reserves at 114,000 million tons.

good coking coal; Santa Clara field has anthracite and semianthracite; number of high-ash seams in Mixteca district.

**Honduras.** Five million metric tons total reserve. All is lignite except one million tons of bituminous coal in El Paraiso district. Beds 1½ to 4 ft thick have never been mined.

**Panama.** Very small deposits of lignite. Submarine deposits in Bocas del Toro, as well as high-sulphur coals inland.

**South America** is apparently deficient in good coal deposits, and very little data are available. Probable total reserves 35 billion tons.

**Colombia.** 21 billion tons in Cauca and Valle districts; 5 billion in Boyacá and Cundinamarca; 1 billion in Antioquia. Coal ranges from medium-grade bituminous to subbituminous. Mines developed only for such local uses as railroads and domestic. Several large unstudied fields have been reported.

**Venezuela.** Only 5 million tons. Lignite and subbituminous. Unexplored fields reported.

**Ecuador.** Negligible amounts reported. Some good coal ranging from lignite to anthracite in province of Cañar. Anthracite at San Antonio de Pomasqui, north of Quito.

**Peru.** Peruvian coal includes 700 million metric tons of anthracite; considerable expansion of this estimate is considered likely. Rather extensive areas running through the Andes Mountains; ranging from low-grade bituminous coal to anthracite. At Chota, 140 miles from Pacific Ocean, there are four anthracite beds 13 to 65 ft thick containing some 700 million tons. Some mines highly gaseous.

**Bolivia.** Practically nothing is known of Bolivian reserves. A few outcroppings of poor seams on Lake Titicaca.

**Brazil**,<sup>1</sup> a country which derives over 60 per cent of its fuel energy from wood and charcoal, is said to have total coal reserves of some 380 to 650 million metric tons. Of this, approximately 80 per cent is located in the state of Santa Catharina, southwest of Rio de Janeiro and south of São Paulo. In general, the coal ranges from subbituminous to medium-volatile noncoking bituminous with some small amounts of semi-anthracite in the southernmost state of Rio Grande do Sol. The coals are usually very high in inherent ash, correspondingly low in heat value, and high in sulphur. Santa Catharina coal, of low- to medium-volatile rank contains 36 to 40 per cent ash and 8 to 12 per cent sulphur in the run of mine. This state has the only known metallurgical coal in Brazil; the Barro Branco seam has strong coking characteristics.

**Argentina.** Thin seams of low-grade bituminous coal along border of Andes. Albertite, a solid resembling coal but derived from petroleum, is found in the province of Mendoza.

**Chile.** Coals are near the ocean and easily accessible, making Chile South America's leading producer, although Colombia greatly surpasses it in reported reserves. Coal is of bituminous rank; much is of inferior quality. Province of Concepción and region near Bay of Aruco are yielding best coal. Submarine mines at Penco.

**British Isles.** Reserves in millions of metric tons: 11,357 Class A; 178,176 Classes B and C. Great Britain is surpassed in production only by the United States and Germany. Great Britain's coal has been a leading factor in her high industrial and commercial position. Because the coal measures of Wales reach a maximum depth of 10 to 12 thousand ft, calculations of reserves depend on depth considered recoverable.

**England and Wales.** Reserves: about 125 billion tons of all kinds. The more than two dozen fields of England and Wales may be grouped into three principal areas, the southern, the central, and the northern. The southern, including fields of South Wales, Forest of Dean, Bristol, and Kent, produce coal varying from bituminous through the well-known Welsh steam coal to anthracite of high quality. The central field, including Lancashire, North Wales, Yorkshire, Derbyshire, Nottinghamshire, Staffordshire, and Warwickshire, produce 30 to 35 per cent volatile gas coals, some of which yield good coke. Cumberland produces a considerable variety of coals such as steam, domestic, coking, gas, and manufacturing. Anthracite of the South Wales field is characterized by low ash; usually clinkers readily.

**KENT.** Good quality, somewhat friable, bulk is steam and domestic, remainder coking.

**LANCASHIRE AND CHESHIRE.** Almost all in gas coal class; some fair coking.

**YORKSHIRE.** Most extensive, most important field in Great Britain.

**BARNSELY.** High-class steam coal.

**MITCHELL MAIN.** Gas coal. 11,500 cu ft.

**STAFFORDSHIRE.** Iron and coal can often be worked from the same pit.

**SHELTON.** Some shafts 3,000 ft deep. Blast furnace, steam and domestic coal.

**DURHAM-NORTHUMBERLAND** coking coals in this field unequalled in Great Britain.

**BOWERS.** Steam coal.

**GARES FIELD.** Coking coal.

**WALLSEND.** Domestic coal (known as "house coal" in England).

**BOLDEN.** Gas coal.

**LITTLE LIMESTONE.** A well-known seam.

**SHILBOTTLE.** One of the best domestic coals in northern England.

**Scotland.** Reserves about 21 billion metric tons actual reserves. Much high-grade bituminous coal and anthracite is mined in Scotland. Cannel coal is abundant in

<sup>1</sup> GOOD, JOHN E., ALVARO ABREU, and THOMAS FRASER, *The Coal Industry of Brazil*, U.S. Bur. Mines Tech. Paper 713, 1949.

some fields, and a peculiar coal known as torbanite, which is a boghead, is mined at Torbane Hill, Scotland.

**AYRSHIRE.** A first-class domestic coal.

**"ANTHRACITIZED" KILMARNOCK SEAM.** Large quantities "anthracitized" by intrusions of igneous rocks.

**LANARKSHIRE.** Most important field of Scotland. Excellent domestic coal.

**FIFE-CLACKMANNON.** Second only to Lanark field in importance.

**DUNFERMLINE SPLINT.** A well-known Scotch coal.

**Ireland.** Reserves; 180 million metric tons of actual reserves, of which all but 8 million tons are anthracitic. The Leinster field, covering 95 sq miles and containing about 150 million tons of good domestic anthracite, is the most important. Others are the Ballycastle, Tyrone, Lough, Allen, and Tipperary.

**TIPPERARY, UPPER-GLENGGOOLE.** An anthracite coal; only 15 million tons reserves.

**CONNACHT OR ARGINA.** Both steam and semianthracite coals are present with but a small amount now being extracted.

**LOUGH NEAGH (COALISLAND).** A concealed, largely unexplored coal field of possible future value.

**Europe (Continental)** contains coal reserves of some 600 billion metric tons of which 47 billion tons are classed as anthracitic and the remainder as bituminous coals to lignite.

**Germany** contains the largest supplies of coal of any of the European countries. The coal is lignite, or *Braunkohle* (brown coal), and bituminous coal, or *Steinkohle*. The six main districts are Ruhr, Aachen, Saar, Upper Silesia, Lower Silesia, and central Germany. Four additional districts contain lignite: Prussia and the north German states, Saxony, Bavaria, and Hesse.

**SAAR.** Hard in structure, adapted to transportation, mining difficult.

**RUHR.** Coal ranges from medium- to high-volatile, and ash varies widely.

**LOWER SILESIA.** Mines faulty and gaseous. Slaty coal; difficult to ignite.

**UPPER SILESIA.** Bulk of coal of first-class coking quality. Used in iron industry.

**POLAND. DABROWA.** Good fuel coal but inferior for gas and iron making on account of long flame.

**CRACOW.** Poorest quality; contains large quantities of ash, slate, and moisture.

**France.** The most important area is Valenciennes with anthracite to high-volatile bituminous coal. Lignite occurs in an important basin known as Fuveau. French deposits are mostly in a large number of small fields.

**Spain.** The most important provinces are Asturias and Leon in the northwest and Tureul in the east. In Asturias a total of 112 ft of coal is broken into as many as 80 seams.

**Portugal.** A small anthracite measure lies near San Pedro de Cova. Medium-quality bituminous coal is reported near Tigueira.

**Belgium.** This country is comparatively well supplied with high-grade bituminous coal. The three fields are Dinant in the south, Namur in the center, and Campine in the north. Coal is contained in a series of strata; the upper runs 35 to 45 per cent volatile, middle 20 to 35 per cent volatile, and the lower less than 20 per cent. The deepest coal mine in the world is at Namur.

**Netherlands.** Best known fields are South Limberg and South Peel. Coals mostly lignite and bituminous with much gas coal.

**Denmark.** Mines, now abandoned, were on Bornholm Island.

**Iceland.** Some coal is mined for local use. (The capital is heated by hot water from thermal springs.)

**Sweden.** Sweden's one small coal field is in the province of Skane in the south. The coal is high-volatile to subbituminous.

Table 1-7. Typical Analyses of Foreign Coals<sup>1</sup> by Fields

Origin	Proximate analysis, <sup>a</sup> per cent					Btu	
	Fixed carbon	Volatile	Ash	Sulphur	Moisture		
<b>Anthracites<sup>b</sup></b>							
British Isles, South Wales field	89 0-92 3	4 3- 5.8	1 7- 2 7	0 8-1 5	0 9- 1.3	14,076,15,023 13,842-14,500 13,500-14,630	
Irish Free State, Leinster field	91 5, 92 3	4 5, 4 7	3 2, 3 8	0 8, 1 5	Dry basis		
Russia, <sup>c</sup> import from Black Sea	89 0-91 3	2 3- 7 1	2 9- 6 5	0 8-3 5	3 2- 3 5		
Indo-China <sup>c</sup>	82 3-93 5	3 3- 7 3	3 1-10 0	0 6-0 8	1 3- 2 4		
<b>Bituminous and Lignite</b>							
<b>British Isles:</b>							
South Wales field	72 8-85 5	10.0-21.2	2 0- 3 5	0 7-1 3	0.9- 1.2	12,284 9,768 14,033	
Kent field	63 7-80 9	14 3-30 8	4 1-11 2	0 8-1.0	Dry basis		
Lancashire and Cheshire	58 9-70 5	26 6-36 2	1 1- 3 6	0 4-2 4	1 1- 4 6		
Yorkshire field	61 1-64 7	28 7-35 3	2 5- 4 5	0 7-1 6	0 7- 2.5		
Barnsley	64 7	28 7	4 1	1 62	2 5	12,284 9,768 14,033	
"Mitchell Main"	64 3	29 5	4 5	1 53	1 7		
Staffordshire	51 6	35 8	1 5		11 3		
Shelton colliery	64 0	30 9	2 5	0 8	1 8		
<b>Durham-Northumberland:</b>							
Bowers (steam coal)...	65 4	29 4	2 5	0 7	2 7	12,284 9,768 14,033	
Garesfield (coking)	67 9	27 7	3 4	0 6	1 0		
Wallsend (domestic)	59 2	32 4	2 6	1 1	5 9		
Bolden (gas coal)	64 7	31 3	2 0	0 9	2 0		
Little limestone	61 3	32 6	4 8	2 0	1 3	12,284 9,768 14,033	
Shilbottle	58 0	33 3	7 2	2 9	1 3		
<b>Scotland:</b>							
Ayrshire	53 2	34 1	2 1	0 6	10 5	12,284 9,768 14,033	
Ayrshire semianthracite..	83 9	11 1	3 2		1 8		
Lanarkshire	66 5	29 1	2 1	0 5	2 3		
Lanarkshire splint	54 3	36 2	2 2		7 7		
Fife-Clackmannon Dunferline splint	73 6	24 3	1 4	0 27		12,284 9,768 14,033	
<b>Irish Free State:</b>							
Tipperary, Upper Glengoose	82 5	3 7	13 8	2 1			
Connacht or Arigna	49 7	26 8	23 5	0 4			
Connacht or Arigna semianthracite	76 8	16 0	7 2	1 6			
Lough Neagh (Coalisland)	53 2	29 8	11 3	1 7	5 7	12,284 9,768 14,033	
<b>Eastern Europe, Germany, and Poland:</b>							
Saar	47 0-60 0	27 5-36 8	7 0-11 0		3 0- 8 0	10,800-12,600 11,000-14,500 11,722 10,800-13,300 11,000-13,200 8,300-11,000	
Ruhr	50 0-72 0	18 0-36 0	4 0-13 0		2 0- 8 0		
Lower Silesia	56 1	25 6	13 8		4 5		
Upper Silesia	45 0-62 0	28 0-33 0	3 0-12 0		2 5- 8 2		
Dabrowa (Poland)	70 6-60 4	15 0-18.0	0 5-1 24	0.5-1 2	9 2-14 0	10,800-12,600 11,000-14,500 11,722 10,800-13,300 11,000-13,200 8,300-11,000	
Cracow (Poland)	45 0-70 0	16 0-20 0	2.7-15 0	.....	6 0-20 0		
<b>France:</b>							
Low volatile ..		9 0-19 0	4 0-12 0	1 0-1 3		10,800-12,600 11,000-14,500 11,722 10,800-13,300 11,000-13,200 8,300-11,000	
High volatile		20 0-38 0	4 0-12 0	1 0-1 3			
Anthracitic		7 0-12 0	1 3-10 0	1 0-1 3			
Lignites		40	15 0-20 0	1 0 1.3			
<b>Belgium</b>							
Bulgaria (lignite)	40 1	38 0	7 5	2 5	14 3	13,900-14,500	
Turkey, Eregh Basin		40 0-45 0	7 0-11 0				
<b>South Africa:</b>							
Transvaal	51 0-61 0	21 0-26 0	12 0-21 0	0 5-2 0	1 0- 6 0	13,900-14,500	
Orange Free State	50 4	28 4	15 6	1 5	5 6		
Rhodesia	66 8	21 0	11 5		0 7		
Natal							
Dundee colliery	70 5	16 6	8 7	4 2	0 5	13,900-14,500	
Navigation colliery	71 6	15 2	11 4	1 3	0 5		
<b>Asia:</b>							
India			10 0-25 0			9,778- 9,939	
Malay Peninsula	39 0-41 2	35.5-38 7	1.0- 5 1		18.0-21.0		
China							

<sup>1</sup> HOAR, H. M., "The Coal Industry of the World," U.S. Department of Commerce, Trade Promotion Series, No. 105, Government Printing Office, Washington, D.C.

<sup>a</sup> Subject to variation because of different testing methods in different countries.

<sup>b</sup> Includes only the more familiar true anthracites; semianthracites not included because of inconclusive nature of many analyses.

<sup>c</sup> Correspondence, U.S. Bureau of Mines, Hudson Coal Co., and others.

**Norway (Spitzbergen).** Norway proper has no coal except a little on some of the northern islands. Spitzbergen has considerable good subbituminous coal mined on Advent Bay by an American company, despite ground frozen to 1,200 ft and a 3-month shipping season.

**Switzerland.** Reserves of probably less than 90,000 tons. Coal has been mined in Switzerland for over 250 years.

**Bulgaria.** Has some anthracite and bituminous in thin irregular seams.

**Hungary.** Brown coals or lignites are the only ones of commercial importance. A considerable amount of the lignite formerly belonging to Hungary is in Croatia and Slavonia.

**Russia.** Low-fusion anthracite (approximately 2200°F) otherwise of good quality.

**Turkey (Eregli Basin).** Considerable coal and lignite; possibly anthracite.

**South Africa. Transvaal.** Coal fields cover about 5,000 sq miles.

**Orange Free State.** Noncoking, fairly good steaming.

**Rhodesia.** Good coking, excellent steaming.

**Natal.** Has anthracitic characteristics, excellent steaming, high sulphur. Well-known collieries are Dundee and Navigation.

**Asia. India.** High ash finely disseminated through the coal. One-third of the coal is coking.

**Malay Peninsula.** Noncoking, fair steaming quality.

**China.** Third ranking country in the world in coal reserves, range from lignite through anthracite.

**Table 1-8. Estimated Proved Crude-oil Reserves of the World<sup>1</sup>**

(As of Jan. 1, 1947)

Country	Billions of bbls	Per cent of total
North America . . . . .	21.9	32.7
United States . . . . .	20.9	31.2
Canada . . . . .	b	b
Mexico . . . . .	0.9	1.3
South America . . . . .	5.2	12.2
Venezuela . . . . .	7.0	10.0
Colombia . . . . .	0.5	0.7
Europe . . . . .	8.2	12.2
U.S.S.R. . . . .	7.6	11.3
All others . . . . .	0.6	0.9
Asia . . . . .	25.4	42.4
East Indies . . . . .	0.9	1.3
Iran, Arabia, Iraq, Kuwait	27.3	40.7
Africa . . . . .	0.1	0.1
World total . . . . .	67.0	100.0

<sup>1</sup> Compiled by Dr. A. C. Fieldner, Chief, Fuels and Explosives Division, U.S. Bureau of Mines, January, 1948.

<sup>a</sup> 42-gal barrels.

<sup>b</sup> Leduc field not included.

### World Petroleum Reserves

According to the "World Oil Yearbook," published in February, 1948, the world grand total of proved oil reserves was estimated at 61,913,652,000 bbl as of Dec. 31, 1947. The annual number of the *Oil and Gas Journal*, published Jan. 29, 1948, shows the world's total as 71,312,000,000 bbl for Dec. 31, 1947. The latter figure is nearly 10 billion bbl higher than the first named estimate. This difference is explained by a statement that the lower figure does not include 9 to 10.5 billion bbl of "indicated and

probable" reserves in the Middle East, which were omitted to make the table comparable on the same classification basis as that of the API for the United States.

### The New Oil Fields of Western Canada<sup>1</sup>

The oil strike of western Canada began in 1947 at Leduc, north of Calgary, Alberta. In October, 1948, a second field was opened at Redwater, 35 miles northeast of Edmonton and only 50 miles from the Leduc field. These two fields, plus strikes in the surrounding area, add up to one of the major North American oil developments of recent

<sup>1</sup> *Time*, Aug. 29, 1949, p. 28.

years. Alberta's known reserves are now estimated at 1 billion bbl, with possible total reserves of several times this.

**Leduc Field.** Estimated reserve: 250 million bbl.

**Redwater Field.** Estimated reserve: 300 million bbl, with 135 producing wells (as of Aug. 29, 1949) and new wells being brought in at the rate of 45 a month.

The 890 wells in the province of Alberta have a capacity of 100,000 bbl a day; this is expected to expand to 300,000 by 1951. However, they are producing only 60,000 bbl daily, with many of the new wells being choked back as they are brought in. This is because of lack of facilities for bringing the oil to large markets at prices competitive with current sources of supply and is thus subject to remedy by the construction of new pipe lines.

### MINERAL-FUEL RESERVES OF THE UNITED STATES<sup>1</sup>

The United States is fortunate in having large reserves of all types of mineral fuels in solid, liquid, and gaseous form. The coal reserves, excluding those of Alaska, but including lignite, were estimated by the Federal Geological Survey at 3.2 trillion net tons as of Jan. 1, 1947. However, these survey estimates represent all coal and lignite underground, much of which is not recoverable by foreseeable methods of mining. As of July, 1948, Dr. Fieldner<sup>1</sup> estimated the recoverable reserves as 50 per cent of the total reserves. Even so, and after allowing for the replacement of all other fuels by coal after the exhaustion of the former, Dr. Fieldner estimates a life expectancy of over 700 years at present rate of utilization, as will be discussed later in this chapter.

The total reserves of coal in the United States are thought to be from 40 to 50 per cent of the world reserves (all ranks of coal).

The proved reserves of petroleum in the United States as of Jan. 1, 1946, were estimated at 20.8 billion bbl by the Committee on Petroleum Reserves of the API. This is about 35 per cent of the proved world reserves.

The proved reserves of natural gas have been subject to a rapid upward revision from year to year, and even from estimate to estimate. The latest available estimate by the Committee on Natural Gas Reserves of the AGA places the proved recoverable reserves at 160.5 trillion cu ft as of Dec. 31, 1946. Very few data are available on the world reserves of natural gas.

In addition to these fuel reserves, D. E. Winchester of the Federal Oil Conservation Board has estimated a potential reserve of 92 billion bbl of oil obtainable from the distillation of oil shale in the United States. This amount is more than four times the present proved petroleum reserve.

**Differences in Methods of Estimating Reserves.** There is an important difference between the estimates of natural gas and petroleum on the one hand and those of solid fuels on the other. Only the proved reserves are given for liquid and gaseous fuels. These are increased each year by new discoveries and extensions of fields and are decreased by the year's production. Since 1940, the petroleum reserve has increased only 2 million bbl; during the same period the estimates of natural-gas reserves increased from 80 to over 160 trillion cu ft. Undoubtedly much more oil and gas will be discovered in the United States, and in this respect these fuels differ from coal and oil shale.

Solid-fuel reserves are estimated from geological measurements of thickness and extent of deposits obtained from surface outcroppings, trenching, exploratory tunnels,

<sup>1</sup> FIELDNER, DR. A. C., Chief, Fuels and Explosives Division, U.S. Bureau of Mines, *Mech. Eng.*, March, 1947, pp. 221-226, 228. Original material revised for this handbook, with figures and comment supplied by Dr. Fieldner on July 7, 1948.



shafts, and drill cores. While no great accuracy can be claimed for these estimates, future exploration is not likely to add greatly to the solid-fuel reserves.

**Relation between the Reserves of Mineral Fuels.** All evidence points to very much larger reserves of coal than of oil and gas, as shown in Table 1-9 and Fig. 1-9, where all the mineral fuels are expressed in equivalent tons of 13,000 Btu coal. The total of all ranks of coal amounts to 1,277 billion tons of 13,000 Btu coal, whereas the

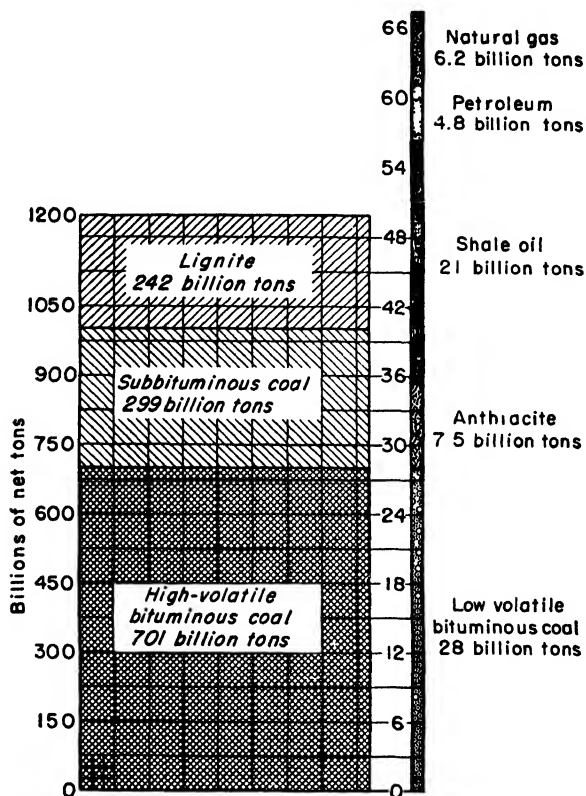


FIG. 1-9. Estimated recoverable mineral fuel reserves of the United States as of Jan. 1, 1947. All fuels expressed in equivalent tons of bituminous coal of 13,000 Btu per lb calorific value. Medium-volatile bituminous coal is distributed between high- and low-volatile coal. (1 small square = 1 billion tons.) (Compiled by A. C. Fieldner, Chief, Fuels & Explosives Division, U.S. Bureau of Mines, January, 1948.)

proved petroleum reserve is equivalent in heating value to only 4.8 billion tons of coal, and the proved natural-gas reserve is equivalent to 6.1 billion tons. Excluding fissionable material, coal comprises 97.5 per cent of our mineral-fuel energy reserves. Oil shale amounts to 1.6 per cent, natural gas to 0.5 per cent, and petroleum to 0.4 per cent.

#### Estimate of Life Expectancy of Fuel Reserves of the United States.<sup>1</sup>

Assuming that  $\frac{1}{2}$  ton of 13,000-Btu coal is required to produce 1 bbl of oil and that  $\frac{1}{15}$  ton of 13,000-Btu coal is required to produce 1,000 cu ft of 1,000-Btu gas, then to

<sup>1</sup> By A. C. FIELDNER, Chief, Fuels and Explosives Division, U.S. Bureau of Mines. Based upon Dr. Fieldner's Table 1-9.

**Table 1-9. Estimated Recoverable Mineral-fuel Reserves of the United States**  
(As computed by Dr. A. C. Fieldner, January, 1948)

Fuel	Reserve, Jan. 1, 1947	Assumed annual produc- tion	Equivalent billions of net tons of 13,000-Btu bituminous coal <sup>a</sup>			Reserve divided by annual produc- tion
			Reserves, Jan. 1, 1947	Per cent total re- serves	Assumed annual produc- tion	
Anthracite, billions of net tons	7 5	0.060	7 3	0.6	0 059	124
Low-volatile bituminous, billions of net tons <sup>b</sup>	26	0.115	28	2.1	0 124	226
High-volatile bituminous, billions of net tons <sup>b</sup> . . . . .	675	0.467	701	53 5	0 485	1,445
Subbituminous, billions of net tons	409	0.014	299	22 8	0 010	
Lignite, billions of net tons	470	0.004	242	18 5	0 002	
Total, all ranks of coal, billions of net tons . . . . .	1,587.5	0.660	1,277	97 5	0 680	1,878
Petroleum, billions of barrels	20.9	1.73	4 82	0.4	0 399	12 1
Oil from shale, billions of barrels	92	1 73	21 2	1 6	0 399 <sup>d</sup>	53 1
Natural gas, trillions of cubic feet	160	4 1	6 15	0 5	0 157	39 2
Total, all fuels . . . . .			1,309		1.236	1,059

<sup>a</sup> Heating values used in conversion. anthracite, 12,700 Btu per lb, low-volatile bituminous coal, 14,000; high-volatile bituminous coal, 13,600; subbituminous coal, 9,500; lignite, 6,700; crude petroleum, 6,000,000 Btu per bbl; gas, 1,000 Btu per cu ft

<sup>b</sup> Includes some medium-volatile coal.

<sup>c</sup> Proved reserves only.

<sup>d</sup> Not included in the total.

supply a current annual production of 1.73 billion bbl of crude petroleum and 4.1 trillion cu ft of natural gas will require the conversion, respectively, of 865 and 373 million tons or a total of 1,138 million tons of 13,000-Btu bituminous coal.

This amount added to the 680 million tons of coal now produced per year would raise the total production of equivalent 13,000-Btu coal required per year to produce all the consumption of solid, liquid, and gaseous fuels from 680 to 1,818 million tons per year—nearly three times the present production.

In round numbers, 58 years<sup>1</sup> is the life of all oil, oil-shale, and natural-gas reserves as sources of the assumed annual production of oil and gas, given in Table 1-9.

In these 58 years the total coal production at the assumed annual rate of 0.680 billion tons of equivalent 13,000-Btu coal would be  $58 \times 0.68 = 39.44$  billion tons, thus reducing the coal reserves to  $1,277 - 39 = 1,238$  billion tons.

Now,  $1,238/1.818 = 681$ , the years of life of coal reserves as exclusive sources of coal, oil, and gas after proved petroleum-oil shale and natural-gas reserves are exhausted; and  $681 + 58 = 739$  years, the total life expectancy of all fuel reserves at present assumed rates of consumption.

#### Location of Coal Reserves of the United States

Of the 3.2 trillion net tons of total coal reserves and 1.6 trillion net tons of recoverable reserve<sup>2</sup> in the United States, less than 10 per cent has been exhausted because of mining and loss in mining.

The United States coal reserves are, for the most part, readily available because of their shallow depth and accessibility to transportation. This is especially true of the

$$\frac{1.482 + 21.2 + 6.15}{0.399 + 0.157} = 57.6.$$

<sup>2</sup> U.S. Geological Survey as of Jan. 1, 1947, and an assumption of 50 per cent as recoverable coal.

Appalachian region, which not only contains high-grade coal but is closest to the Atlantic seaboard and therefore more available for oversea trade. In contradistinction to this advantage, the average haul of American coal from mine to ship is very much longer than that of British coal, which rarely exceeds 20 miles.

**Table 1-10. Percentages of Various Ranks of Coal Comprising Total Coal Reserves of the United States<sup>1</sup>**

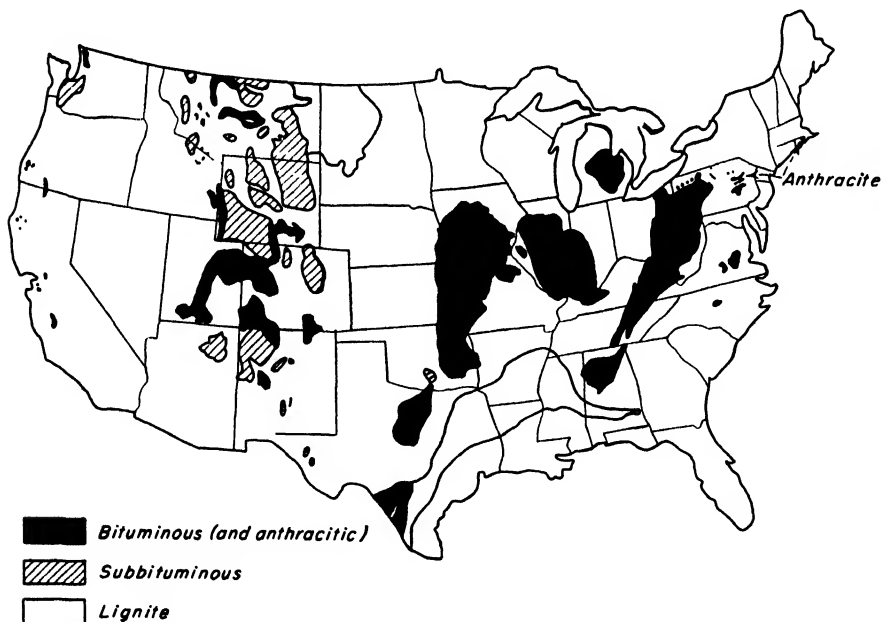
Rank	Per Cent of Total Reserves in Equivalent Tons of 13,000-Btu Coal
Anthracite.....	0 5
Low-volatile bituminous.....	2 5
High-volatile bituminous.....	55 0
Subbituminous.....	23 0
Lignite.....	19 0
Total.....	100 0

<sup>1</sup> FIELDNER, A. C., *The National Fuel Reserves*, *Mech. Eng.*, March, 1947, p. 221.

The minimum thickness of beds included in the Geological Survey estimate of reserves is 14 in. for bituminous and anthracitic coals, 2 ft for subbituminous coal, and 3 ft for lignite. Coal beds lying more than 3,000 ft below the surface were not included in the estimates.

On the basis of energy content, the total coal reserves are distributed among the different ranks of coal in the proportions indicated in Table 1-10.

**Coal-bearing Areas of the United States.<sup>1</sup>** The coal-bearing areas of the United States have been divided by the U.S. Geological Survey into six main provinces, designated as the Eastern province, Interior province, Gulf province, northern Great



**Fig. 1-10.** General location of the coal fields of the United States. (*Coal Age*, April, 1943.)

Plains province, Rocky Mountain province, and Pacific Coast province. The provinces are subdivided into coal regions, coal fields, and coal districts.

The **Eastern province**, which contains probably nine-tenths of the high-rank coal of

<sup>1</sup> CAMPBELL, M. R., AND OTHERS, *The Coal Fields of the United States*, *U.S. Geol. Survey, Profess. Paper 100-A*; "The Coal Industry of the World," U.S. Department of Commerce, Trade Promotion Series, No. 105, Government Printing Office, Washington, D.C., 1930.

the country, embraces the anthracitic regions of Pennsylvania and Rhode Island; the Atlantic Coast region includes the Triassic fields of Virginia and North Carolina; and the Appalachian region extends from northern Pennsylvania into Alabama, and also comprises considerable areas of Ohio, Maryland, Virginia, West Virginia, eastern Kentucky, Tennessee, and Georgia. **The Appalachian region may be regarded as a huge depository of bituminous and semibituminous coals of the highest rank.**

The **Interior province** includes all the bituminous areas of the Mississippi Valley region, and the coal fields of Texas and Michigan. This province is subdivided into the northern region, containing only the coal field of Michigan; the eastern region, comprising the fields of Illinois, Indiana, and western Kentucky; the western region, embracing the coal fields of Iowa, Missouri, Nebraska, Kansas, Arkansas, and Oklahoma; and the southwestern region in Texas. **With the exception of the semianthracite coal of Arkansas and high-rank bituminous coal of Oklahoma, the coals of this province do not compare favorably in quality, as a whole, with those of the Eastern province.** But, owing to its vast resources, good mining conditions, and proximity to large markets, there have been notable developments and a continuous expansion of output.

The **Gulf province** is subdivided into the **Mississippi region** in the east and the **Texas region** in the west. The former embraces the lignite fields of Alabama, Louisiana, and Mississippi; and the latter those of Arkansas and Texas. Up to the present, the Gulf province coal resources have been commercially unimportant, the mining of lignite being carried on only at a few points west of the Mississippi to furnish fuel for domestic use and for manufacturing purposes. East of the Mississippi, however, there has been no such incentive, as coal of excellent quality is mined in great abundance within easy reach. **Much of the lignite of the Gulf Coast is rich in volatile matter and is regarded as a form of cannel coal, particularly above Laredo, Tex., where it has been mined for several years as a cannel coal of bituminous rank.** In 1925, the estimated original reserve of Texas lignite was placed at 23,000,000,000 tons and of bituminous coal at 8,000,000,000 tons, of which considerably less than 75,000,000 tons has been mined.

The **northern Great Plains province** includes all the coal fields of the Great Plains east of the eastern front range of the Rocky Mountains. Included are the immense lignite areas of the two Dakotas, the estimated original reserves of which total 600,000,000,000 tons, and the bituminous and subbituminous fields of northeastern Wyoming and northern and eastern Montana. Vast areas with tremendous tonnage are included, but the **coals are of low rank**, with the exception of a few basins adjacent to the mountains.

The **Rocky Mountain province** comprises the coal fields of the mountainous districts of Montana and Wyoming, and all the coal fields of Utah, Colorado, and New Mexico. It possesses a greater variety of coals, ranging from lignite to anthracite, than any other province in the United States. Some of the best grade coals occur mainly in Colorado, which contains the **largest and most important fields of bituminous coal west of the Missouri River**, and in Utah, Wyoming, and New Mexico. Although considerable progress has been made, vast areas still await further exploitation.

The **Pacific Coast province** is not divided into regions, being limited largely to the state of Washington, which contains the largest coal fields on the Pacific Coast, but also embracing small fields in Oregon and California. Reserves of the former were estimated in 1925 at 54,442,000,000 tons, while those of the latter stood at only 23,000,000 tons. The largest coal area lies south of Tacoma and extends southward across the Columbia River a short distance into Oregon. While some of these coals are bituminous, **the great bulk possesses the characteristics of subbituminous.** Largely because of the coals of higher rank nearby and in Vancouver Island, and also

because of a high percentage of ash in Washington coals, development has been retarded.

The coals of Oregon and California rank somewhat lower than those of Washington. Oregon's coal reserves are very limited, more than two-thirds is subbituminous, it is difficult to mine, and much of it lies below sea level. The remaining third is bituminous and coking coal, but it is shaly and dirty in some localities. California coals consist mainly of noncoking bituminous coal in the southern part of the state, lignite in the northern, and subbituminous in the center. Since the coal fields are limited in area as well as widely scattered, the immediate future holds forth little prospect that California will become a worth-while coal-mining state.

To review the coal reserves of the United States, the East dominates in quality, the West in quantity. Considered from the viewpoint of quantity only, the heaviest coal reserves in the United States occur in the three Western areas known as the northern Great Plains, Rocky Mountain, and Pacific Coast provinces, whose deposits far surpass in quantity those of the two Eastern provinces. In fact, the Fort Union region of Wyoming, Montana, and the Dakotas possesses the largest quantity of coal known in any single coal-bearing area, aggregating 1,104,103,000,000 tons. The next greatest reserve area is that of the Green River region of Wyoming and Colorado, with deposits amounting to 665,649,000,000 tons. The third is that of the Appalachian region of the East with reserves totaling 550,989,000,000 tons.

Nevertheless it is in the Eastern and Interior provinces that the real wealth of coal lies. Approximately 98 per cent of all United States anthracite, and the best steaming coal, the semibituminous, is limited practically to the two Eastern provinces. The coals of the central and northern fields of the Appalachian region supply the bulk of the coke produced, furnish power for concentrated industrial activities, constitute the heaviest portion of our shipments to Canada, and provide most of our exports.

Table 1-11. Coal Reserves of Various Ranks Distributed by Provinces<sup>1</sup>

(Billions of net tons)

Provinces	Anthracitic	Bituminous	Subbituminous	Lignite	Totals
Eastern. . . . .	15 1	525 2			540 3
Interior . . . . .	0 2	508 0		0 1	508.3
Northern Great Plains, Rocky Mountain, and Gulf . . . . .	0 1	360 3	763 9	939 4	2,063 7
Totals . . . . .	15 4	1,393 5	763 9	939 5	3,112 3

<sup>1</sup> FIELDNER, A. C., The National Fuel Reserves, *Mech. Eng.*, March, 1947.

**Distribution of Reserves, by Types of Coal.** Only one-third of the total tonnage of coal and lignite reserves occurs in the Eastern and Interior provinces. Two-thirds is found in the Great Plains and Rocky Mountain provinces.

However, there is a great difference in rank between the Eastern and Western coals. Practically all the Eastern and Interior province coals, except the anthracitic coals, are caking bituminous coals; and the Appalachian region coals are strongly coking. This region supplies most of the coking coals used in the United States. On the other hand, 80 per cent of the Great Plains and Rocky Mountain coals are subbituminous and lignite.

Most of the bituminous coal in the Western states is free-burning and noncaking. Relatively small deposits of coals suitable for the production of metallurgical coke occur in the Trinidad-Raton field of southern Colorado and northern New Mexico, the Sunnyside beds in the Castlegate field of Utah, and in Pierce and Kittitas Counties,

Washington. Some of the coals are slightly caking but do not become plastic enough to form coke that is sufficiently strong for use in the iron blast furnace.

In general, anthracite and coking coals of metallurgical grade occur in the Eastern province, coking coals of lower grade and lower bituminous rank in the Interior province, and noncaking coals of lignitic, subbituminous, and bituminous rank in the Great Plains and Rocky Mountain provinces.

**Type of Reserves by States.** Pennsylvania coals are largely bituminous, with 98 per cent of the country's reserves of anthracite. All of West Virginia's coals are bituminous, including low-, medium-, and high-volatile bituminous coal. West Virginia has the greatest reserves of the best grade and highest rank of bituminous coal of any state in the Union; Pennsylvania is second. Illinois has the greatest tonnage of bituminous coal, but it is inferior in grade and rank to the Appalachian coals. The coals of Illinois, Iowa, Missouri, Kansas, western Kentucky, and Indiana are inferior to the Appalachian coals for the production of metallurgical coke and are but little used for this purpose. The Ohio coals grade between the Illinois and West Virginia coals.

**Table 1-12. Distribution of Solid-fuel Reserves of the United States<sup>1</sup>**

(In billions of net tons)

Order of reserves	State	Anthracite	Bituminous coal	Subbituminous coal	Lignite
	Alabama		66 5		
	Arkansas	0 2	1 3		0 1
3	Colorado	0 1	212 6	104 0	
	Georgia		0 9		
	Idaho and Oregon		0 7	1.8	
5	Illinois		197 2		
	Indiana		51 8		
	Iowa		28 7		
	Kansas		29 6		
7	Kentucky		121 0		
	Maryland		7 7		
	Michigan		1 9		
	Missouri		83 6		
4	Montana		2 6	62 9	315 5
	New Mexico		18 8	1.9	
	North Carolina		0.1		
2	North Dakota				600 0
	Ohio		91 7		
	Oklahoma		54 7		
8	Pennsylvania	14 9	65 6		
	South Dakota				1 0
	Tennessee	.. .	25 2		
	Texas	.. .	8 0		22 9
	Utah	.. .	87 9	5.2	
	Virginia	0 5	20 5		
	Washington	.. .	11 2	52.4	
6	West Virginia		110 5		
1	Wyoming		30 3	590 0	
	Total	15.7	1330 0	818 0	939.5

Grand total 3,103 billion tons

<sup>1</sup> HENDRICKS, T. A., U.S. Geological Survey, from Senate Hearings on Investigation of National Resources before a Subcommittee of the Committee on Public Lands and Surveys, 80th Cong., 1st sess., May, 1947, pp. 232-235.

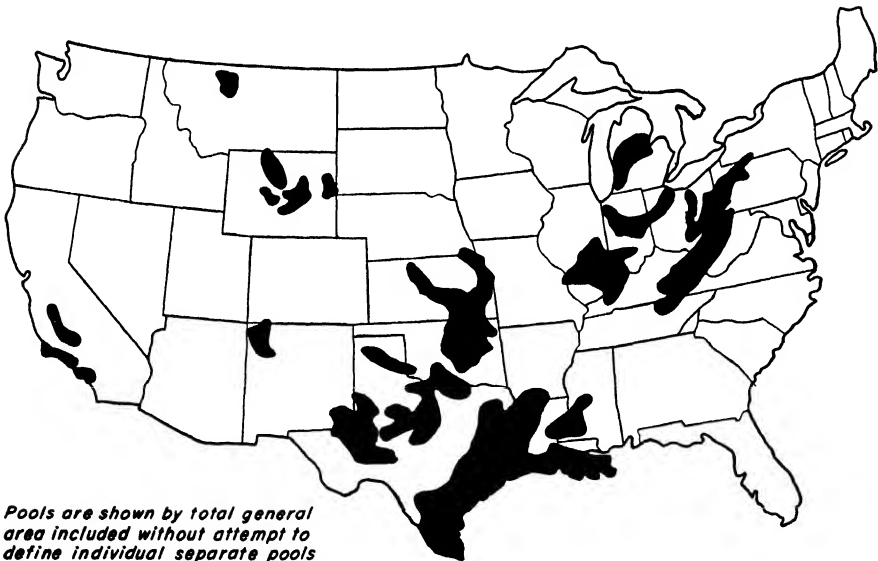
On a Btu basis, Wyoming has the largest reserves, with 590 billion tons of subbituminous coal and 30 billion tons of bituminous coal. North Dakota is second on the heat-value basis with 600 billion tons of lignite; Colorado is third with 213 tons of

bituminous coal and 104 billion tons of subbituminous coal; and Montana is fourth with 316 billion tons of lignite, 63 billion tons of subbituminous coal, and 3 billion tons of bituminous coal. These four states contain 51 per cent of the nation's energy reserves in the form of coal and lignite.

**Table 1-13. Comparison of Coal Reserves of Certain States<sup>1</sup>**  
[Billions of net (2,000 lb) tons]

State	U.S. Geological Survey		State geological survey		
	Tons	Minimum thickness of bed, in.	Tons	Minimum thickness of bed, ft	Per cent of U.S.G.S.
Illinois . . . . .	197 8	14	167 0	2	84
West Virginia . . . . .	147 7	14	113 5	1	77
Pennsylvania bituminous . . . . .	103 3	14	75 0	1	73
			41 3	2	40
Pennsylvania anthracite. . . . .	15 0	..	15 8	..	105
Kansas . . . . .	29 7	14	17 6	1	59

<sup>1</sup> Compiled by Dr. A. C. Fieldner, Chief, Fuels and Explosives Division, U.S. Bureau of Mines, January, 1948.



*Pools are shown by total general area included without attempt to define individual separate pools*

**FIG. 1-11. Known oil-producing areas of the United States. Pools are shown by total general area included without attempt to define individual separate pools. (Power, September, 1944.)**

#### Petroleum Reserves of the United States

The almost static position of the petroleum reserves in the United States has become a matter of great concern and much speculation as to the future. It is true that the proved reserves, 20,827,000,000 bbl in 1946, are the (then) highest in the history of the country. However, for the six years 1940 to 1946, the annual rate of increase was only 390,000,000 bbl. Offsetting this gain, the use of oil for space heating rose 50 per

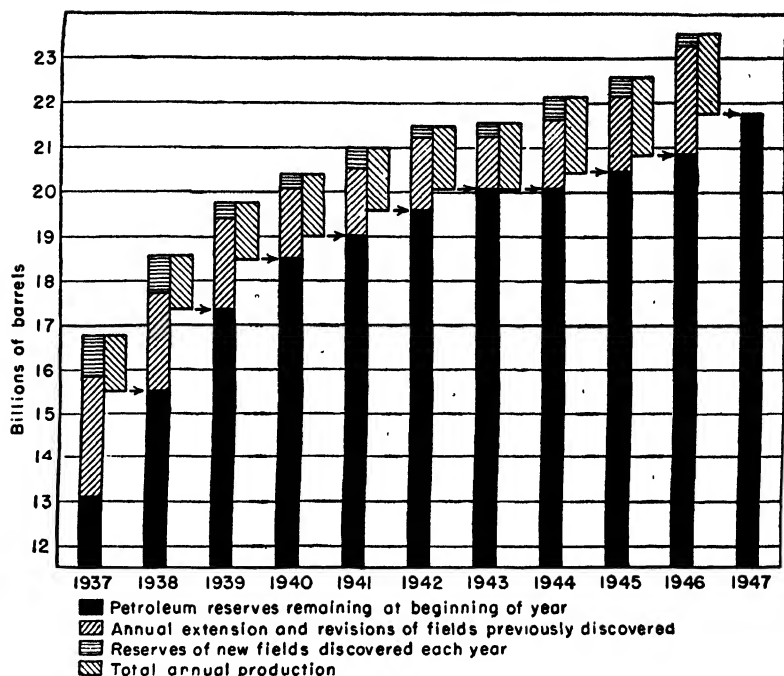


FIG. 1-12. History of United States petroleum reserves, 1937 to 1946, inclusive. (Compiled by A. C. Fieldner, January, 1948.)

Table 1-14. Estimated Proved Reserves of Liquid Hydrocarbons<sup>1</sup>

(In millions of barrels as of the beginnings of the years shown)

Year	Crude oil	Natural-gas liquids			Total liquid hydrocarbons
		Conden- sate	Natural Gasoline and LPG <sup>a</sup>	Total	
1945	19,784	669	b	b	b
1946	19,942	885	b	b	b
1947	20,873	1,051	2,303	3,354	24,227

<sup>1</sup> Proved Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas, Joint Report of AGA and API, Dec. 31, 1946, p. 12.

<sup>a</sup> LPG = liquefied petroleum gas.

<sup>b</sup> Data not available.

Table 1-15. Estimate of Proved Oil Reserves by States, 1946<sup>1</sup>

(Million barrels)

Eastern states.	773
Illinois . . . . .	350
Indiana. . . . .	41
Kentucky . . . . .	57
Michigan . . . . .	64
New York . . . . .	81
Ohio . . . . .	30
Pennsylvania . . . . .	110
West Virginia . . . . .	39
Central and Southern states.	15,675
Arkansas . . . . .	304
Kansas . . . . .	542
Louisiana . . . . .	1,690
Mississippi . . . . .	267
New Mexico . . . . .	512
Oklahoma . . . . .	890
Texas . . . . .	11,470
Mountain states . . . . .	948
Colorado . . . . .	280
Montana . . . . .	108
Wyoming . . . . .	600
Pacific Coast states. . . . .	3,410
California . . . . .	3,410
Other states . . . . .	2
Total United States.	20,327

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1945.



cent in the two postwar years to an all-time high of 320 million bbl; and automotive vehicles rose 45 per cent in 10 years to a 1948 rate of 670 million bbl. Obviously a static, or nearly static, reserve supply in the face of rapidly rising demand and consumption can only result in a depletion of domestic reserves unless bolstered by importation of foreign oil, restricted by more economical or frugal use, or supplemented by synthetic oils. In 1948 our imports exceeded exports (174 as against 154 million bbl) for the first time.

With reserves at 20.8 billion bbl<sup>1</sup> and current consumption at approximately 1.8 billion bbl a year, it is obvious that our present reserves are sufficient for only 12 years. However, it is inconceivable that no new discoveries will be made, and as their extent is entirely a matter of speculation, as is the question of future demand, it is impossible to predict the future with even a reasonable degree of accuracy.

### Natural-gas Reserves of the United States

The Committee on Natural Gas Reserves of the AGA released its first annual report on proved recoverable reserves in 1946 to cover the year 1945. These figures for 1946 are shown in abbreviated form in Table 1-16.

**Table 1-16. Estimated Proved Recoverable Reserves of Natural Gas in the United States<sup>1</sup>**  
(As of Dec. 31, 1946)

State	Millions of cu ft*			
	Nonassociated	Associated	Dissolved	Total
Alabama . . . . .	.....	.	97	97
Arkansas . . . . .	447,651	162,276	261,735	871,662
California . . . . .	3,687,430	3,198,714	4,240,157	11,126,301
Colorado . . . . .	155,440	41,075	119,248	315,763
Illinois . . . . .	3,000	55,000	210,000	268,000
Indiana . . . . .	4,000	8,000	5,000	17,000
Kansas . . . . .	13,257,617	212,310	210,917	13,257,617
Kentucky . . . . .	1,299,000	.	87,000	1,386,000
Louisiana . . . . .	18,323,314	2,697,126	1,391,071	22,411,511
Michigan . . . . .	76,200	.	54,800	131,000
Mississippi . . . . .	1,731,821	446,098	192,594	2,370,513
Montana . . . . .	853,401	.....	.....	853,401
Nebraska . . . . .	.....	.....	1	1
New Mexico . . . . .	3,079,900	2,132,911	691,975	5,904,786
New York . . . . .	69,000	.....	900	69,900
Ohio . . . . .	573,000	.	41,000	614,000
Oklahoma . . . . .	7,572,279	1,589,538	1,574,028	10,735,845
Pennsylvania . . . . .	453,000	.	50,000	503,000
Texas . . . . .	62,345,192	15,282,025	8,736,242	86,363,459
West Virginia . . . . .	1,739,000	.....	101,000	1,840,000
Wyoming . . . . .	693,191	235,176	107,230	1,035,597
Florida, Missouri, and Utah . . . . .	76,900	.	321	77,221
Total . . . . .	116,440,336	26,060,249	18,075,316	160,575,901

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946 preprint. Reserves of dissolved gas were estimated jointly by Committee on Natural Gas Reserves, AGA, and API Committee on Petroleum Reserves.

\* Volumes are reported at pressures of 14.65 psia and at a standard temperature of 60°F.

Proved reserves of natural gas, as defined by the committee, "include the gas in both the drilled and undrilled portions of the fields. The undeveloped areas considered to have proved reserves are those so located with respect to the field geology

<sup>1</sup> An unofficial estimate in *The Lamp* (Esso Standard Oil Co.) for March, 1948, places 1947 reserves plus natural-gas liquids at 24,700,000,000 bbl.

and structure that production therefrom is virtually assured. Recoverable reserves of natural gas are the reserves estimated to be producible under existing operating practices."

**Types of Natural-gas Reserves.** The three types into which natural-gas reserves have been divided are defined as follows:

1. Nonassociated gas is free gas not in contact with crude oil in the reservoir.
2. Associated gas is free gas in contact with crude oil in the reservoir.
3. Dissolved gas is gas in solution in crude oil in the reservoir.

**Effect of Pressure on Gas Reserves.** As natural gas is compressible the pressure at which reserves are calculated is an important factor in determining quantities. The AGA uses 14.65 lb abs at 60°F.

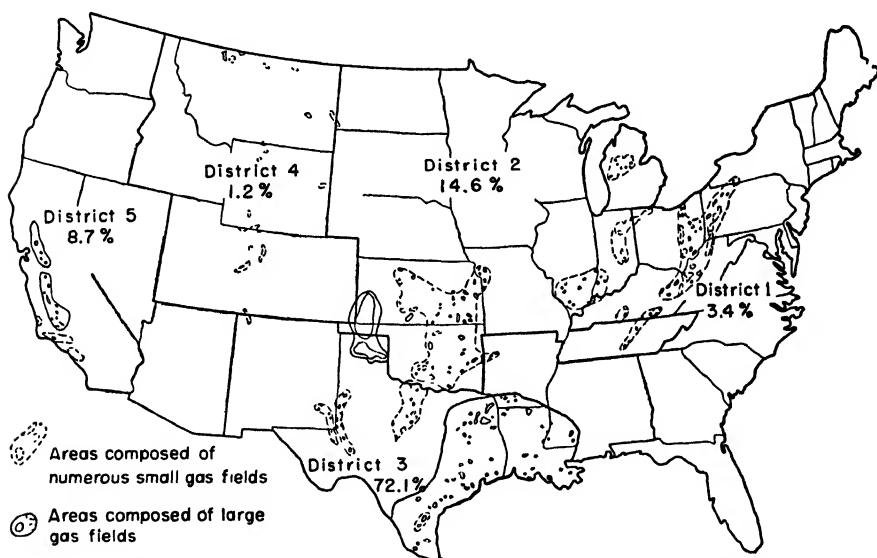


FIG. 1-13. Major gas-producing areas in the United States. (Compiled by Dr. E. L. DeGolyer, from Federal Power Commission, Docket G580, Exhibit 445.)

**Location of Fields and Extent of Reserves.**<sup>1</sup> As natural gas is inherently a limited and exhaustible resource, primary importance attaches to the extent and location of reserves, both existing and in prospect.

Figure 1-13 shows the distribution of natural-gas reserves in the United States and emphasizes the extent to which these reserves are heavily concentrated in the Appalachian, Mid-Continent, Gulf Coast, and California areas. This concentration is further demonstrated in the inset of Fig. 1-14, showing that the Southwest area accounts for nearly three-fourths of all the presently known reserves of natural gas.

Figure 1-14 shows the growth of proved reserves of natural gas within the period 1920 to 1945. In 1920 the then known reserves amounted to only some 15 trillion cu ft. Subsequent estimates show a steady rise of proved reserves to 145 trillion cu ft at the beginning of 1946. It must be noted that these can only be rough approximations by experts, accurate and final figures being utterly impossible, even though scientific methods of estimating have greatly improved in recent years.

<sup>1</sup> FEDERAL POWER COMMISSION, Statement on Natural Gas for the House Committee on Interstate and Foreign Commerce with Reference to House Joint Resolution 2 on Disposition of the Big Inch and Little Big Inch Pipe Lines, Jan. 23, 1947.

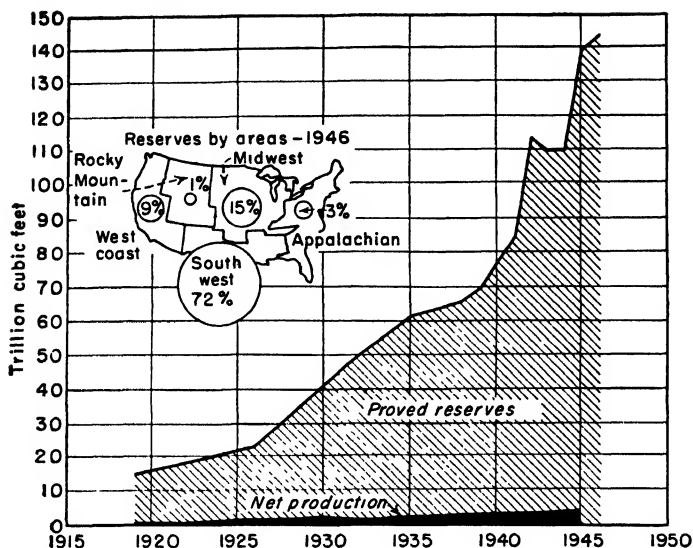


FIG. 1-14. Natural-gas reserves in the United States vs. net production. (Note: Presentation similar to PAW Chart 26 in report "Natural Gas and Its Products During the War," by James E. Pew.) (Federal Power Commission, Docket G580, Exhibit 445.)

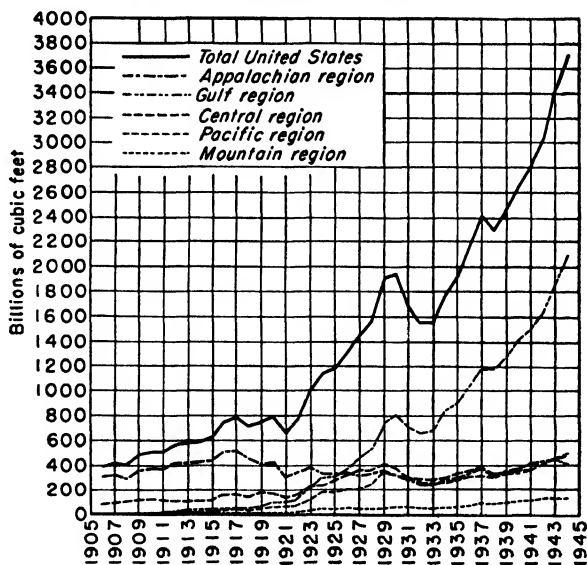


FIG. 1-15. Marketed production of natural gas in the United States by regions, 1906 to 1944. (U.S. Bureau of Mines.)

The trend of future discoveries is essentially uncertain. It is considered unlikely, however, that important deposits will not continue to be found.

**Rate of Production as Related to New Discoveries.** Despite very substantial and almost uninterrupted increases in marketed production, the additions which have been made to reserves have substantially exceeded net production in each 5-year

period since 1920. The net additions to reserves, moreover, were greatest in the recent period from 1941 to 1945, wherein the additions to reserves amounted to about 80 trillion cu ft as compared with net production of some 20 trillion cu ft. As a consequence, the "reserve life index" of the gas fields has increased from some 15 years in 1920 to 30 years in 1945. The direction of this trend in the future will depend upon the ratio of additional proved reserves to the volume of net production.

**Marketed Production of Natural Gas.** Trends in the marketed production of natural gas, for the United States and by regions, over the period 1906 to 1944, are shown in Fig. 1-15. It is shown that the marketed production increased from less than 700 billion cu ft in 1921 to over 3,700 billion cu ft in 1944. Most of this increase is accounted for by the Gulf Coast region, although substantial increases were also made in other regions.

**Long-distance Transmission of Gas.** The development of long-distance transmission lines to move natural gas from its concentrated sources of supply to industrial areas, which began in about 1928, has reached a point where over 1 trillion cu ft of gas yearly moves to distant markets in 33 states and the District of Columbia. Figure 9-5 shows the constant growth of this pipe-line mileage.



## CHAPTER 2

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### GENERAL CHARACTERISTICS OF SOLID FUELS<sup>1</sup>

<b>Classification of Coals by Rank.....</b>	<b>34</b>
<b>Petrographic Constituents of Coal.. . . .</b>	<b>34</b>
Types of coal. Practical effects of various properties of coal. Fusibility of coal ash. Ash-softening temperatures and ash composition. Underfeed stokers. Pulverized coal. Water-gas sets. Composition of coal ash. Friability and size stability of coal.	
<b>Miscellaneous Solid Fuels .....</b>	<b>48</b>
Torbanite. Byerite. Parrot coal. Horn coal. Carbonite. Albertite. Graphite.	

<sup>1</sup> Grindability and drying, being processes of preparation rather than characteristics, are treated in separate sections.

Whenever possible to separate the material, the characteristics of the several fuels have been treated in the respective individual chapters.

**Table 2-1. Classification of Coals by Rank<sup>1</sup>**  
(F.C. = fixed carbon. V.M. = volatile matter)

Class	Group	Limits of fixed carbon or Btu mineral-matter-free basis	Requisite physical properties
I. Anthracite	1. Meta-anthracite	Dry F.C. 90 % or more (dry V.M. 2 % or less)	Nonagglomerating <sup>a</sup>
	2. Anthracite	Dry F.C. 92 % or more and less than 98 % (dry V.M. 8 % or less and more than 2 %)	
	3. Semianthracite	Dry F.C. 86 % or more and less than 92 % (dry V.M. 14 % or less and more than 8 %)	
II. Bituminous <sup>b</sup>	1. Low-volatile	Dry F.C. 78 % or more and less than 86 % (dry V.M. 22 % or less and more than 14 %)	Either agglomerating or nonweathering <sup>c</sup>
	2. Medium-volatile	Dry F.C. 69 % or more and less than 78 % (dry V.M. 31 % or less and more than 22 %)	
	3. High-volatile A	Dry F.C. less than 69 % (dry V.M. more than 31 %). Moist Btu 14,000 <sup>d</sup> or more	
	4. High-volatile B	Moist Btu 13,000 or more and less than 14,000 <sup>d</sup>	
	5. High-volatile C	Moist Btu 11,000 or more and less than 13,000 <sup>d</sup>	
III. Subbituminous	1. Subbituminous A	Moist Btu 11,000 or more and less than 13,000 <sup>d</sup>	Both weathering and nonagglomerating
	2. Subbituminous B	Moist Btu 9,500 or more and less than 11,000 <sup>d</sup>	
	3. Subbituminous C	Moist Btu 8,300 or more and less than 9,500 <sup>d</sup>	
IV. Lignitic	1. Lignite	Moist Btu less than 8,300	Consolidated Unconsolidated
	2. Brown coal	Moist Btu less than 8,300	

<sup>1</sup> Standard Specifications for Classification of Coals by Rank (ASTM D388-38, ASA M20.1-1938). This classification does not include a few coals that have unusual physical and chemical properties and that come within the limits of fixed carbon or Btu of the high-volatile bituminous and subbituminous ranks. All these coals either contain less than 48 per cent dry mineral-matter-free fixed carbon or have more than 15,500 moist mineral-matter-free Btu.

<sup>a</sup> If agglomerating, classify in the low-volatile group of the bituminous class.

<sup>b</sup> It is recognized that there may be noncaking varieties in each group of the bituminous class.

<sup>c</sup> Moist Btu refers to coal containing its natural moisture but not including visible water on the surface of the coal.

<sup>d</sup> Coals having 69 per cent or more fixed carbon on the dry mineral-matter-free basis shall be classified according to the fixed carbon, regardless of Btu.

<sup>e</sup> There are three varieties of coal in the high-volatile C bituminous coal group, viz., variety 1, agglomerating and nonweathering; variety 2, agglomerating and weathering; variety 3, nonagglomerating and nonweathering.

## PETROGRAPHIC CONSTITUENTS OF COAL

According to the U.S. Bureau of Mines,<sup>1</sup> coal is composed essentially of three classes of constituents—anthraxylon, attritus, and fusain.

**Anthraxylon** (vitrain in British nomenclature) occurs as glossy black bands in bituminous coal that represent undisintegrated but coalified trunks and limbs of trees and plants, and portions thereof. Some of the original plant cell structure is revealed in thin sections under the microscope. Anthraxylon (vitrain) is the principal con-

<sup>1</sup> U. S. Bur. Mines Tech. Paper 666, pp. 11-17, 1944.

stituent of bright coals, and numerous anthraxylon bands can usually be seen in a lump of bright coal.

**Attritus** is the ground mass of plant debris in which the anthraxylon bands or strands are embedded. In thin sections the attritus is translucent, opaque, or of various gradations between these limits. Numerous remains of plant entities may be recognized in translucent attritus when magnified 100 diameters or more. Chief among these are spore and pollen exines (coats), cuticles of leaves and stems, resin particles, and remains of algae in boghead coal. Opaque attritus is virtually opaque to transmitted light in medium-thin sections under the microscope, but as the sections are ground thinner more of the constituents become translucent, although some always remain opaque, no matter how thin the section may be ground. Next to fusain, opaque attritus seems to be the most inert constituent of coal.

**Fusain** is the black, fibrous, charcoal-like material, also known as mother of coal or mineral charcoal, which is found in various ranks of coal in lenses and layers of all sizes, from those visible only at high magnification to those 2 in. or more in thickness.

### Types of Coal

The petrographic types of coal, as defined in U.S. Bureau of Mines practice, are given in Table 2-2.

The **bright coals** comprise the greater part of the nation's coal reserves and sometimes are referred to as "common banded coals." In thin sections, the numerous anthraxylon bands are seen to be separated by translucent attritus. The latter may consist of any of the constituents previously mentioned, such as leaves, spores, resins, cuticles, and translucent degradation matter. The bright coal corresponds to the coal referred to in English nomenclature as **vitrain** plus **durain**.

Table 2-2. Types of Coal by Petrographic Constituents<sup>1</sup>

Types of Coal	Relative quantity of anthraxylon and attritus	Nature of attritus	Structure of coal
Bright	Anthraxylon predominating to attritus predominating	Translucent attritus predominating, opaque attritus present	Banded; bright luster
Semisplint	Anthraxylon and attritus in more or less equal proportions	Translucent attritus and opaque attritus in about equal proportion	Compact; finely banded
Splint.	Attritus predominating	Opaque attritus predominating; translucent attritus (especially spores) present	Banded; compact; hard; irregular fracture; dull luster
Cannel. . .	Almost all attritus	Translucent attritus (often spores) to opaque attritus predominating	Compact; hard; conchoidal fracture; dull luster; non-banded
Boghead	Almost all attritus	Translucent attritus (oil algae) predominating; opaque attritus present	Compact; hard; conchoidal fracture; dull luster; non-banded

<sup>1</sup> FIELDNER, A. C., AND ASSOCIATES, Research on the Hydrogenation and Liquefaction of Coal and Lignite, *U.S. Bur. Mines Tech. Paper* 666, p. 12, 1944.

**Splint and Semisplint Coals.** Splint coals (durain in British nomenclature) commonly have a dull luster, grayish-black color, and compact structure. They are hard and tough and break with an irregular, rough, sometimes splintery fracture into large lumps and slabs that stand transportation remarkably well. They are characterized by a semiopaque to opaque ground mass or attritus, whereas the bright-coal sections have a ground mass or attritus that is predominantly translucent.



If the content of opaque attritus ranges from 20 to 30 per cent the coal is classified as **semisplint**; if more than 30 per cent, it is classified as **splint** coal.

**Cannel and boghead coals** are clean, nonbanded, compact, blocky coals of massive structure and uniform fine-grained texture. Usually they are dark gray to black, display a greasy luster, and have a noticeably conchoidal or shell-like fracture. As shown in thin sections under the microscope, these coals are composed almost entirely of attritus, with very few bands of anthraxylon. The attritus may comprise a wide variety of components, such as spore and pollen exines, anthraxylon debris, oil algae, and opaque constituents. The preponderance of one or two constituents usually determines the type.

**Boghead-cannel coals** have chemical properties similar to those of spore-cannel coals but differ microscopically in having an appreciable quantity of oil algae in addition to the spores and other constituents of a normal cannel coal. If the oil algae comprise nearly all the ground mass, the coal is termed a **boghead coal**.

### Practical Effect of Various Properties of Coal<sup>1</sup>

Coal is a complex mixture of organic and inorganic materials. The chemical identity of only a few of these components is known. That the mixture must be variable in composition is evidenced by the wide variance in the properties of different coals. In fact, coals vary from one another by such imperceptible gradations of the several properties that the number of combinations is infinite. Some of these properties vary in known relation to each other, while others vary quite independently. Because of all such factors, the interpretation of laboratory tests on coal is extremely complex and, in fact, nearly always resolves itself into a matter of the relative performance or value of one coal as compared with another. The interpretation of laboratory tests on coal is rendered still more difficult by the wide variety of conditions to which coal is subjected in use. It thus becomes a problem of relating different combinations of properties of coal to a great variety of combinations of conditions of use.

In a most comprehensive attempt to correlate these several factors the National Association of Purchasing Agents made a study of several years' duration leading to the report "Factors Recommended for Consideration in the Selection of Coal." This is reprinted here in its entirety by permission of the association as Tables 15-10 to 15-19. While the use of specific figures in the report would have had obvious advantages, this was found to be impossible because of the complexity of the study. The several properties of coal are thus graded as to relative importance in relation to many uses and conditions of use.

**Relative Effect of Properties of Coal Dependent upon Plant Characteristics.** The effect of variation in any one or combination of physical and chemical properties of coal is likely to be relatively small within limits determined by the physical characteristics of each plant. As these limits are approached or exceeded, the adverse effect becomes rapidly more pronounced. For this reason, the relation of the properties of coal to the capacity at which a plant must be operated is often of paramount importance, and in general is of greater importance in selecting coal for existing plants than are variations in efficiency or operating cost.

**Plant Characteristics of Major Importance.** The temperature of the fuel bed and furnace, and the rate at which coal must be burned per square foot of grate or per cubic foot of furnace constitute the principal factors determining the relative importance of the properties of coal. The following plant characteristics should be given particular attention:

<sup>1</sup> GOULD, G. B., in "Symposium on Significance of Tests of Coal," *ASTM, Proc.*, vol. 37, Part II, pp. 341-466, 1937.

1. Furnace volume and design
2. Grate area
3. Water cooling of walls and amount of radiant heating surface

Any deficiency in furnace volume or grate area, or in equipment for crushing, pulverizing, or feeding of fuel, tends to accentuate the importance of the chemical and physical properties of coal.

### Factors Affected by Properties of Coal

The several properties of coal may singly or in combination affect either (1) the efficiency of the plant, (2) its operating cost, (3) its maximum output, or (4) any combination of these.

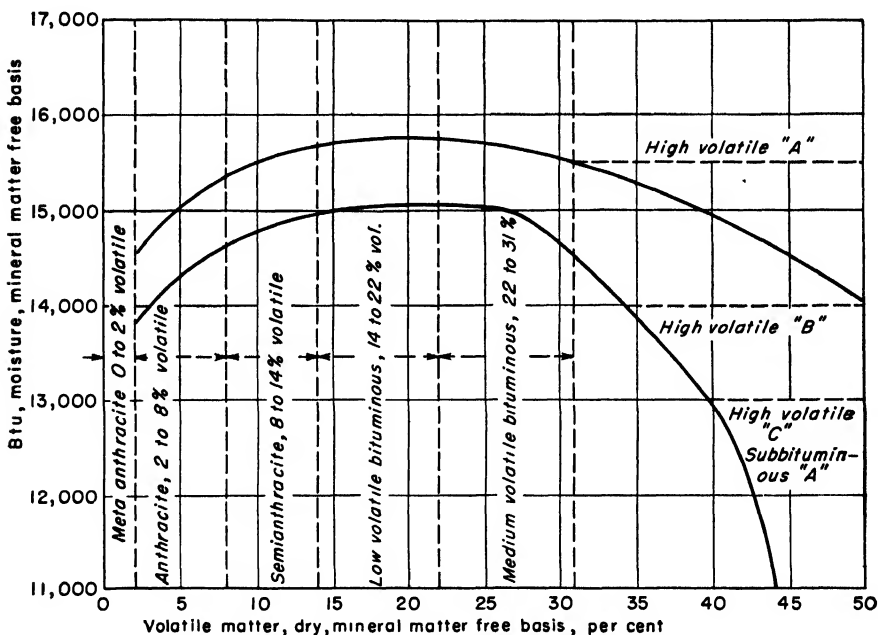


FIG. 2-1. Classification of coals of the United States by rank. (Note: The range of values are as shown between the two curves.)

**Calorific Value.** Of all laboratory tests applied to coal, the calorimetric test is the only one which provides a measure of its intrinsic value as a fuel. The result, as expressed as either British thermal units (United States and Great Britain) or calories per gram (metric countries),<sup>1</sup> in addition to being the only quantitative measure of the energy value of coal as a fuel, has a relation also to the operating cost and maximum steam output of a plant. Variations in Btu in a given plant are ordinarily of primary importance from the standpoint of the total energy received and usually of only secondary importance for their effect on operating cost or capacity. However, this varies greatly among plants, since in a large steam station, operating all or part of its units at maximum capacity, coal having a lower Btu might necessitate operating

<sup>1</sup> Definitions as found under Thermal Value of Fuels, p. 363, show basically that 1 Btu equals the amount of heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit; 1 gram-calorie, 1 gram of water 1 degree Centigrade.

more units, or result in failure to meet the maximum demand. The great majority of industrial plants have a margin of unused capacity which is greater than the ordinary variations in Btu. Failure to carry the load is more often due to the effects of some of the other properties of the fuel.

In comparing two coals of different Btu the handling costs of both coal and ashes must be taken into consideration.

**Relation between Btu and Rank of Coal.** It is desirable to understand, in a general way, the relation which exists between the Btu and the rank of a coal, even though the Btu per pound of "pure" coal, which is a theoretical abstraction, has no direct application in the interpretation of a coal analysis. This is shown in Fig. 2-1, where it will be seen that the Btu, volatile matter, fixed carbon, and moisture are all interrelated.

As the percentage of volatile matter rises, the Btu per pound of pure coal first rises and then declines. Up to about 35 per cent volatile matter (dry mineral-matter-free basis), variations in the natural bed moisture (inherent moisture) are small, and the percentage of volatile matter is the primary indication of rank, and correspondingly of the range of Btu per pound of pure coal. From about 35 per cent volatile matter upward, the amount of natural bed moisture increases substantially, becomes a significant indicator of rank, and correspondingly decreases the Btu value.

The reason for the relation between the Btu value and the percentage of volatile matter is that, while the Btu value of fixed carbon remains constant, that of the volatile matter varies considerably according to its composition.

In general, the coal from a given mine has a characteristic Btu value for the pure (ash-free) coal, but there are differences among the sizes, especially the very small sizes, from the same mine. This is due to the fact that the coal is not homogeneous and the smaller sizes may contain a disproportionate share of the more friable material, notably fusain, which is relatively low in Btu value.

From a **geographical standpoint**, the lowest percentage of volatile matter is found in the most easterly of our coal beds, and rises westward to the Mississippi River. Beyond the Mississippi, coals with a wide range of volatile are found in close proximity, notably in Oklahoma, Arkansas, Colorado, and Washington. In the East, there is a gap between the semianthracite and the lowest volatile bituminous coal, from about 11 per cent volatile matter (dry mineral-matter-free basis) to about 14 per cent. Otherwise the progression from low to high volatile is continuous.

**Moisture.** Moisture must be considered both for its effect on plant performance and for its relation to other measurements and calculations.

**Moisture in coal affects the efficiency** of a steam-generating unit directly, only to the slight extent of the heat content of the steam resulting from its evaporation, at the temperature of the flue gases at the exit of the steam-generating unit. This loss is approximately 0.1 per cent of efficiency for 1 per cent of moisture in the coal.

**High surface moisture**, moisture mechanically retained on the surface of the particles or between them, adversely affects the performance of some pulverizers, chiefly by reducing their capacity. Its importance depends upon the closeness of the operating capacity to the maximum capacity of the pulverizer.

The **addition of surface moisture to coking coals** before firing has a distinct beneficial effect on the structure of the fuel bed, particularly in the absence of mechanical agitation as on traveling grates. Observations indicate a higher efficiency, as yet to be measured, resulting from the greater uniformity and porosity of the fuel bed, and an increase in the rate of ignition.

**"Tempering" Coal by Wetting.** For some types of combustion, particularly on traveling- or chain-grate stokers, a certain percentage of moisture is useful in tempering the fire to produce such improved combustion conditions as a reduction of carbon loss to the ashpit and a reduction of clinker.

According to *Combustion Engineering*, the moisture content of bituminous coal for such stokers should lie between 14 and 18 per cent as fired. As this is usually considerably above the "as-received content," moisture must be added, preferably at least 12 hr before the fuel is burned (to allow time for the moisture to permeate the lumps as well as the fines).

With anthracite, a lower percentage is used, with probable maximum efficiencies at about 4 per cent. In reporting the effect of dust, Stenger stated that "wetting the dust-bearing coal practically doubled the air flow. With anthracite, moisture beyond 12 to 14 per cent may lead to difficulties in capacity, efficiency, and ignition."

The use of steam introduced through small pipes in the hopper or coal chutes is more effective than spraying the fuel in the hopper with water at the last minute. Steam jets in the incoming air streams have also been used effectively for the same purpose.

High surface moisture, on the other hand, may adversely affect the flow of coal in bunkers, spouts, and other conveying devices. Difficulties due to freezing are also magnified.

The capacity of coal to retain surface moisture is determined chiefly by the size of the pieces and the uniformity of size. For example, the amount of moisture normally retained by the several commercial sizes of anthracite rises as the size diminishes. Because of the relatively wide range of sizes, the capacity of bituminous coal to retain surface moisture is greater, but it also offers greater resistance to the penetration of moisture in transit or storage. When such coal is rehandled during a heavy rain, it may pick up a comparatively large amount of water, which it will then stubbornly retain during subsequent storage.

High surface moisture in combination with sulphur promotes corrosion of all metal surfaces with which the coal comes in contact during transportation or storage.

With the exception of anthracite, where an arbitrary allowance for moisture is made in **weighing coal at the mines**, it is common commercial practice to **ignore the percentage of moisture in the coal** at the time railroad-car weights are determined. Whatever the moisture content is at that time, it is billed to the buyer as coal.

The use of water cleaning may add to moisture content of a coal, but methods are in use to dewater the coal after cleaning.

The inherent instability of the moisture content of coal introduces a practically inescapable probable error in calculations of steam-plant performance of at least 1 per cent, and in many cases twice as much, unless the moisture is determined from samples taken and sealed at the time the coal is weighed to the boilers.

**Ash Content.** Ash is the incombustible mineral material which remains after the coal has been burned. It is not identical with material commonly referred to as "ashes" or "refuse" which are materials as removed from the furnace and invariably containing proportions of unburned coal.

As the proportion of ash increases, the proportion of heat-producing material decreases, and the Btu per pound of a given coal diminishes proportionately.

The effect of a lower or higher Btu content due to ash content should properly be considered under heading of Btu.

Adverse effect on efficiency is found chiefly in the case of solid-fuel beds, resulting from the entrainment of carbon by the ash, but in all plants ash may affect efficiency by fouling the heating surfaces.

High ash, owing to the additional bulk of material that must be handled to deliver a given number of Btu, reduces the capacity of all fuel- and ash-handling and fuel-burning equipment. Capacity may also be reduced by fouled heating surfaces, reduced draft, or reduced efficiency.

Operating costs are also influenced by the percentage of ash, because of additional

quantities of fuel and refuse to be handled and disposed of; erosion by fly ash of equipment between the furnace and the stack; increased cost of power and maintenance of pulverizers; and increased cost of cleaning.

The percentage of ash has a much greater relative effect on the amount of refuse to be handled than on the amount of coal used. For example, in using 5 and 10 per cent ash coals, the latter will involve the handling of more than twice as much refuse, while the amount of coal used will be only 5 per cent greater.

Likewise the effect in the fuel bed is proportionate not to the amount of coal being consumed but more nearly to the amount of incombustible material present.

**Decrease in Efficiency Due to Increased Ash Content.** Data derived from a study of 400 steaming tests conducted by the U.S. Geological Survey in 1904 to 1906 indicate that the drop in efficiency of boiler and furnace is approximately 0.20 per cent for each 1.0 per cent increase in the ash. These were all hand-fired boilers at low rates of combustion.

More recent tests on chain-grate stokers by B. M. Thornton, of Imperial Chemical Industries, Ltd., England,<sup>1</sup> resulted in somewhat similar conclusions. The results

were interpreted as showing about  $\frac{1}{3}$  of 1 per cent decrease in efficiency for each 1 per cent increase in ash content. In cases where the loss of carbon in ashes is not carefully controlled, and where the coal is of such poor quality that appreciably greater draft is required to maintain output, the effect on efficiency may be somewhat greater.

This relationship refers only to the effect of ash through entrainment of unburned fuel. It does not mean that of two coals differing in percentage of ash, as well as in other properties, the efficiency of the steam-generating unit will necessarily be lower with the coal having the higher percentage of ash. Other properties, such as size or coking characteristics, may nullify the higher ash loss through lower dry-flue-gas losses.

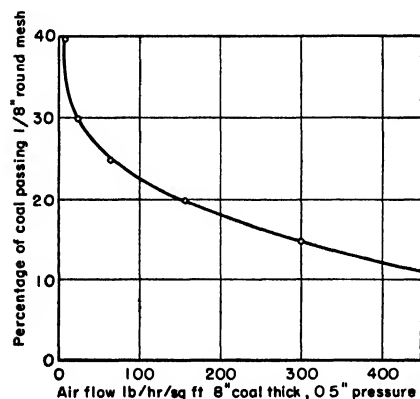


FIG. 2-2. Relative air flow through coal of varying dust content. (Cochrane Corp., Philadelphia.)

**Effect of Undersize in Coal.** Figure 2-2, based upon tests by L. A. Stenger,<sup>2</sup> shows the rate of air flow through coals having different percentages of dust content. The shape of this curve serves as an illustration of the accepted fact that uniformity of sizing is one of the most important points in connection with the combustion of some types of coal, most particularly the small sizes of anthracite. With more than 20 per cent undersize, the resistance of the fuel bed to the flow of air rises so rapidly as to change all combustion characteristics completely.

With **anthracite**, the effect of dust is severalfold. It is difficult to maintain a uniform fuel bed because of the segregation of fines and the consequent blowing of holes in the fire; and the fines impede the flow of air to increase any tendency toward clinker and reduce combustion rates. In addition, fly ash and siftings are usually in direct proportion to the quantity of fines.

With certain types of **bituminous-coal** firing, fines are also of importance, particularly if they are present in the form of dust. In such cases as underfeed and multiple-

<sup>1</sup> GRUMELL, E. S., The Evaluation of Fuel from the Consumers' Viewpoint, *J. Inst. Fuel*, August, 1932, p. 361.

<sup>2</sup> "Finding and Stopping Waste in Modern Boiler Rooms," The Cochrane Corp., Philadelphia.

retort stokers, such fines tend to limit capacity, produce spotty fires due to segregation, and aggravate any tendency to clinker.

In analyzing undersize content, an important point that is frequently overlooked is that the character of the fines is equally, if not even more, important than their percentage. Thus, if a given percentage of fines is almost all dust, serious difficulties may ensue; if, however, a large percentage of the fines is just slightly under the minimum screen size, considerably better results may be secured. It is thus suggested that sizing tests be reported with sufficient detail to permit an appraisal of their nature.

For example, in reporting the undersize in No. 2, or rice anthracite, undersize could be expressed in the three fractions:

1. Per cent of No. 3 buckwheat (through  $\frac{3}{16}$  over  $\frac{3}{32}$ )
2. Per cent of No. 4 buckwheat (through  $\frac{3}{32}$  over  $\frac{3}{64}$ )
3. Per cent of No. 5 buckwheat (through  $\frac{3}{64}$ )

Such a report would show whether the undersize is mostly dust, or whether it is merely a mixture of rice and barley, which would be expected to give better results.

**Volatile Matter and Fixed Carbon.** Small differences in the percentage of volatile matter are usually of little significance in practice.

Pure coal (moisture- and mineral-matter-free) is empirically divided between volatile matter and fixed carbon. That portion of the coal which is driven off as gas by heating (to 950°C for 7 min) is considered the volatile matter. The remainder, exclusive of moisture and mineral matter, is considered to be the fixed carbon. This is a laboratory method for distinguishing between that part of the coal which burns as a gas, and that part which is burned as a solid.

As a practical matter, **coal constitutes a mixture of fuels**, each one having distinct chemical and physical properties. The proportions of gaseous and solid-fuel constituents of coal vary over a wide range from anthracite with the lowest percentage of volatile, through the bituminous coals, to lignite and finally peat.

The proportion of total heat value contributed by the volatile matter in bituminous coals will range from about 25 to 40 per cent. Since the heat produced by the volatile matter is quickly available, the higher volatile coals are generally considered more "flashy" and better adapted to meeting sudden increases in load. Other properties of coal, however, such as the coking characteristics as they affect the porosity of the fuel bed, the size of the coal, and the ignition temperature of the solid part of the fuel, also affect this adaptability to sudden demand.

The consideration of volatile matter is a consideration of major importance in coal selection in plants inadequately designed for the prevention of smoke (see *The Formation and Prevention of Smoke*, page 454).

Viewed solely from the standpoint of the percentage of volatile matter, those coals having the higher percentage of volatile matter are better adapted to burning in pulverized form. Other properties of coal which vary independently of the volatile, such as grindability, percentage of moisture, and the coking or noncoking nature of the coal, also affect its adaptability to pulverizer service and in particular cases may substantially modify this broad generalization.

The percentage of volatile matter, in combination with other determinations, serves to identify a coal with a certain section of the coal fields, a group of mines, a seam, or its rank.

In ordinary commercial practice the percentage of **fixed carbon** carries no direct significance of its own. Being essentially the complement of the percentage of volatile matter, the latter serves as an indication of the two factors

**Sulphur in coals**<sup>1</sup> occurs mainly as sulphide of iron, commonly known as **pyrites**, and as **organic sulphur**. A small amount of it also occurs as **sulphates**.

<sup>1</sup> KRIESINGER, HENRY, in "Symposium on Significance of Tests of Coal," *ASTM Proc.*, vol. 37, Part II, p. 369, 1937.

In a boiler furnace the sulphide of iron generally burns to iron oxide and  $\text{SO}_2$  or  $\text{SO}_3$ . In a reducing or partly reducing atmosphere all the iron and sulphur may not be completely oxidized, and some ferrous sulphide, low oxides of iron, or even metallic iron may be formed. The organic sulphur also burns to  $\text{SO}_2$  or  $\text{SO}_3$ , which are gases and pass with the gaseous products of combustion to the stack. It is believed that some one-third of the sulphur burns to  $\text{SO}_3$ , which at temperatures up to about  $300^\circ\text{F}$  can combine with water vapor (condensed) to form sulphuric acid.

**Corrosion.** The products of the oxidation and decomposition of the sulphur compounds are corrosive and may accelerate the deterioration of all metallic parts with which they come in contact. This includes both the coal- and ash-handling equipment. Generally the higher the proportion of water vapor in the products of combustion the more serious is the corrosion of such parts as economizers, air heaters, flue ducts, and steel stacks.

**Air Pollution.** The products of combustion and decomposition of sulphur compounds flowing out of the stack add an obnoxious odor to the waste gases, thus adding to the objection of polluting the air. Sherman<sup>1</sup> also points out that a similar pollution

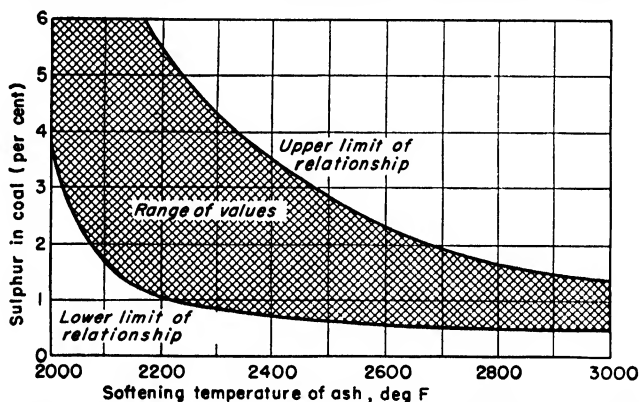


FIG. 2-3. Relation between percentage of sulphur in coals and ash-softening temperature (Pennsylvania coals). (Chart is based upon analyses by W. A. Selvig and A. C. Fieldner contained in "Fusibility of Ash from Coals of the United States," U.S. Bureau of Mines, Bulletin 209, 1922.)

of gases that back up from the stoker hopper can be equally objectionable. Breathing such polluted air is unhealthy and irritating. Sulphur gases are also destructive to metals, stone, concrete, and to paint; they are also destructive to plant life.

In the London district of England, power plants are required by law to remove the sulphur compounds from stack gases before they are discharged into the atmosphere. Although similar legal steps have not been reported in the United States, sulphur in fuel does constitute a serious phase of air pollution.

**Clinkering.** While the exact part played by sulphur in clinkering and slagging is controversial, there is little doubt that sulphur, and particularly the pyrites form, is a contributing factor.

The sulphur and the iron with which the sulphur is combined are apt to lower the softening temperature of the ash, thereby aggravating clinker in the fuel bed, slagging of the furnaces, and slagging and fouling of the heating surfaces. Figure 2-3, plotted from analyses of Pennsylvania coals in U.S. Bureau of Mines Bulletin 209, shows that coals of high softening temperature usually have low sulphur content but that not all low-sulphur coals have high-fusion-temperature ash. However, most high-sulphur

<sup>1</sup> SHERMAN, R. A., Battelle Memorial Institute.

coals have low-softening-temperature ash. Although no definite relation can be deduced, the chart justifies the statement that sulphur is at least a contributing factor in the formation of clinker and slag.

**Slagging and fouling** of the heating surfaces require frequent operation of soot blowers and lances, usually reduce steaming capacity by hindering both combustion and heat absorption, and damage the grate and furnace to increase maintenance costs.

**Sulphur in Pulverized-coal Furnaces.** Because of the uniform distribution of the pyrites and other sulphur compounds in pulverized coal, together with such other factors as high furnace temperatures, slagging is often aggravated in this type of equipment. Nicholls<sup>1</sup> also called attention to difficulties in slag-tap furnaces due to sulphur. Particles of ferrous sulphide reach the bed of molten slag without being oxidized; being denser than the slag, they sink and form a molten mass. When the furnace is tapped, the molten sulphide may be exposed to the air, where it will burn, causing very objectionable and, in some instances, dangerous conditions. Nicholls also pointed to frequent difficulty because of molten masses of metallic iron at the bottom of the beds of slag-tap furnaces, and he attributed this to ferrous sulphide. He felt that particles reaching the surface of the bed, together with particles of carbon, were reduced to iron; this iron, being denser than the sulphide, sinks too low to be removed by tapping and ultimately has to be drilled out.

**Pyrites Stalactites.** Instances have been encountered where concentrations of pyrites in the coal caused the formation of stalactites hanging from the grates, and of such size that shutdowns for chipping were necessary.

**Effect of Sulphur on Storage.** While the exact effect of high sulphur on storage troubles is also somewhat controversial, here again it is undoubtedly at least a contributing factor in spontaneous combustion.

**Fusibility of Coal Ash.**<sup>2</sup> Determination of fusibility of coal ash consists of melting a cone of the ash to a fluid state under specified conditions.<sup>3</sup> Three critical temperatures are observed during the test:

1. *Initial Deformation Temperature.* The temperature at which the first rounding or melting of the point of the cone begins. Warping, shrinking, or bloating should not be confused with the true initial rounding or melting.

2. *Softening Temperature.* The temperature at which the molten mass of the cone becomes a spherical lump. This temperature is the most important because it is the most easily reproduced in the laboratory and is also most easily compared with the conditions existing in the fuel bed of the furnace. It is sometimes incorrectly called the "ash fusion" or "fusion temperature."

3. *Fluid Temperature.* The temperature at which the molten mass of the cone has spread out into a flat layer over the refractory base.

The softening temperature of coal ash from coals of the United States<sup>4</sup> ranges from 1900 to 3110°F. For convenience, the order of fusibility may be expressed by dividing this range into three classes:

*Class I. Refractory ash, softening above 2600°F.*

*Class II. Ash of medium fusibility, softening between 2200 and 2600°F.*

*Class III. Easily fusible ash, softening below 2200°F.*

**Ash-softening Temperatures and Ash Composition.**<sup>5</sup> (See also Clinker Formation and Control, Chap. 11, page 374.) Although the fusibility of ash gives an indication

<sup>1</sup> NICHOLLS, PERCY (deceased), formerly Supervising Engineer, U.S. Bureau of Mines Experiment Station, Pittsburgh.

<sup>2</sup> Analyses of Pennsylvania Anthracitic Coals, *U.S. Bur. Mines Tech. Paper* 659, p. 41, 1944.

<sup>3</sup> *ASTM, Standards*, Part III, 1942, pp. 29-32.

<sup>4</sup> SELVIG, W. A., and A. C. FIELDNER, "Fusibility of Ash from Coals in the U.S.A.," *U.S. Bur. Mines Bull.* 209, 1922.

<sup>5</sup> GAUGER, A. W., in "Symposium on Significance of Tests of Coal," *ASTM, Proc.*, vol. 37, Part II, 1937.



of possible clinker and slag trouble, it is generally agreed that it is not a positive criterion, because no simple direct correlation with ash-softening temperature has been found. This is not surprising in view of the fact that the temperatures in the fuel bed of a modern power plant are hot enough to soften the ash of almost any coal.

In the standard test for ash-softening temperature, there is a **tolerance** of considerable magnitude in test results. Thus the permissible variation on a given sample in the same laboratory is 30°C (54°F) and, as between different laboratories, 50°C (90°F). It is thus obvious that correlation between performance and laboratory results cannot be expected to recognize differences in ash-softening temperatures of less than 180°F.

A second factor is the **variation in the coal samples** themselves. Morrow and Proctor,<sup>1</sup> after an intensive study, reported that, in the case of car samples, *if a sufficient number of samples are taken*, the probable error will be well within the tolerance of the standard test but that the maximum deviation between individual samples may be as high as 500°F for certain sizes.

As a result of an intensive study, Nicholls and Selvig<sup>2</sup> reported that the tendency to form clinker for the average of all tests for each coal used has a very general relation to the softening temperature of the ash but that values for individual coals departed materially from the average curve. Coals having ashes whose fusion temperature was at the low or high end of the ash-fusion-temperature scale conformed to the average more closely than did those in the center having softening temperatures of 2400 to 2600°F.

S. H. Viall is quoted as having determined that analysis of at least 20 samples of a commercial shipment of a given size of coal is required before a reasonably close average value can be obtained for that coal.

A third factor is the **variation in the mineral matter as contained in coal**. Mineral composition is related in a complex way to the ash-softening temperature; and also in a complex way to clinker formation. Unfortunately, however, there are few data on the latter.

A fourth factor is the **different chemical compositions** of ash, which may result in the same ash-softening temperatures but which may also result in slags of widely different fluid properties. Thus silica and alumina may be looked upon as the refractories in the ash, whereas the predominant fluxing materials are lime and iron oxide.

However, despite the lack of direct correlation, as has been pointed out by Nicholls and Selvig, no other single factors for the fusibility of the ash would give any better coordination than does the ash-softening temperature.

Other factors which should be given weight as determining the tendency to clinker (apart from equipment considerations) include size of coal, size consist of coal, its caking and coking characteristics as affecting the paths of the ash through the fuel bed, and the proportion of the ash which is segregated in lumps.

The significance of ash fusion as related to individual classes of equipment is summarized as follows:

**Underfeed Stokers.** It is emphasized that many factors in addition to the softening temperature play equally important roles in the formation of clinkers.

Gould and Henderson, and more recently Tobey, plotted the relationship between softening temperature and clinker trouble. (Fig. 2-4). It was the experience of these authors that, within this band, the probability of escaping clinker was proportionate to the distance to the upper limit and vice versa. Clinker was almost invariably encountered at or below the lower limit and practically never encountered at or above the upper limit. The chances for clinker were about even at the center line of the shaded zones. The data

<sup>1</sup> MORROW, J. B., and C. P. PROCTOR, Variables in Coal Sampling, *Proc. AIME*, vol. 116, pp. 227-269, 1936.

<sup>2</sup> NICHOLLS, P., and W. A. SELVIG, "Clinker Formation as Related to the Fusibility of Coal Ash," *U.S. Bur. Mines Bull.* 364, 1932.

were derived from industrial steam plants of 1,000 to 5,000 bhp, a good proportion of which were equipped with underfeed stokers. They were operated with about 12 per cent carbon dioxide and used coals from the northern Appalachian region (Gould) in run-of-mine or slack size. Introducing a larger amount of excess air would permit the use of lower fusion point coal at the expense of efficiency. A refractory arch or Dutch oven would act in reverse to cause clinker with higher fusion coals, etc. The tendency to form clinkers will increase as the density of the fuel bed increases. A higher combustion rate can therefore be obtained without clinker trouble with a given fusion point with coal which has been screened to exclude the fines. Tobey used both high- and low-volatile coals from the Eastern and Southern fields. It must be stressed that these results are those for specific conditions which might vary considerably in other instances. For example, Gould states that Middle Western coals, particularly those from Illinois, do not conform in practice to the relationship shown in the chart (Fig. 2-4). He states that, for a given combustion rate, the Illinois coal will not cause clinker trouble, with a fusing point at least 200°F lower than coals of similar size from the northern Appalachian field.

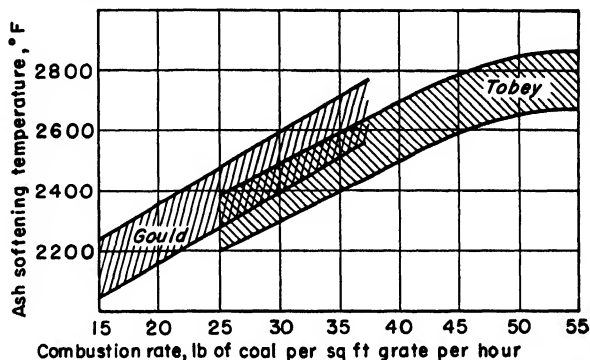


Fig. 2-4. Relation of ash-softening temperature to combustion rate. (Gauger, *ASTM*, 1937.)

It appears that coals which do not coke strongly form another exception. Furnace design, firing practice, and ash composition may also affect the clinkering point.

Bennett and Herbeck<sup>1</sup> described a water-cooled underfeed stoker which successfully burns a coal of ash-softening temperature of 1900°F at a rate of 52 psf of air-admitting surface per hour. Careful air distribution might accomplish the same results because of the cooling effect on the grates. Rosin<sup>2</sup> concluded that control of temperature in the fuel bed and in the gases of the combustion chamber, control of atmosphere, and control of motion of fluid slag offer the weapons of firing technique against the clinker problem.

**Pulverized Coal.** In the case of pulverized coal, the trouble experienced is mainly due to slag formation on the water tubes and to the slagging of the refractories in the combustion chamber. Pulverized-coal installations are of the dry-bottom and the slag-tap types. Whereas coals with a high ash-softening temperature might command a premium in stoker or dry-bottom equipment, they would be useless in the slag-tap installation. Just the reverse would be true in the case of coals with low ash-softening temperature. Bailey and Hardgrove<sup>3</sup> state that "the slag-tap furnace can be successfully used for all coals where the ash has a fusing temperature below 2500°F."

Many factors are involved in the successful burning of coal in pulverized-fuel installations. The composition and softening temperature of the ash are in general less indicative of possible trouble than are furnace and slag-pit construction and furnace rating.

To maintain the boiler-tube bank in a slag-free condition, the temperature of the gases entering the boiler-tube bank should approximate the fusion temperature of the ash. Temperatures somewhat higher are permissible in some cases, depending on the spacing of the first few rows of tubes and the number of vertical rows of tubes.

Iron sulphide seems to be a disturbing element with some slag-tap installations.

<sup>1</sup> BENNETT, J. S., and C. J. HERBECK, Design and Development of a Watercooled Underfeed Stoker, *Mech. Eng.*, December, 1935, pp. 761-765.

<sup>2</sup> ROSIN, P., The Ash Problem in Combustion, Zehnte technische Tagung des deutschen Braunkohlen-Industrie-Vereins, E. V., April, 1931, *Braunkohle*, vol. 31, pp. 628-644, 1931.

<sup>3</sup> BAILEY, E. G., and R. M. HARDGROVE, The Slag-tap Furnace and Its Effect on the Selection of Coal for Burning in Pulverized Form, *Proc. 3d Intern. Conf. Bituminous Coals*, vol. 2, pp. 349-369, 1931.

**Water-gas Sets.** In the operation of the blue-gas generator the alternate blasting and steaming of the fuel causes a temperature cycle that reaches a maximum at the end of the blast and a minimum at the end of the run. Since clinker is formed by the solidification

**Table 2-3. Heat Release at Various Ash-fusion Temperatures<sup>1</sup>**  
(Btu per cu ft of furnace volume per hr)

Wall construction	Ash-fusion temperature, deg F			
	2200°F and below	2200–2400°F	2400–2600°F	Above 2600°F
Solid walls	Never	12,500	15,000	15,000
Air cooled walls	12,000	15,000	17,500	18,500
Water-cooled bottoms	16,000	17,500	20,000	22,000
Water walls . . .	17,500	22,000	30,000	32,000
Complete water-cooled furnace	19,000	24,000	32,000	36,000

<sup>1</sup> GAUGER, A. W., in "Symposium on Significance of Tests of Coal," *ASTM, Proc.*, vol. 37, Part II, 1937.

of a fused slag, the coals with high ash-softening temperature will form clinker high up on the generator lining; those with low ash-softening temperature will yield a slag that remains fluid on the grates to form the very troublesome pancake clinker. On the other hand, those with medium ash-softening temperatures will fuse in the hot zone and solidify on the way down to the grates. The use of up-and-down steaming can be applied to vary the position of the clinker to assist materially in the ease of cleaning the generator. Up steam creates a hot zone in the upper part of the fuel bed, and vice versa.

The fusing temperature of the ash bears a definite relation to the quantity of air that can be blasted through the fire during a blow. With a softening temperature as low as 2200°F the blasting rate per square foot of grate per blow should not exceed 350 to 400 cu ft. As the softening temperature approaches 2600°F, the blasting rate can be increased to a figure as high as 500 to 550 cu ft.

**Composition of Coal Ash.** There are nine components in coal ash that influence the softening temperature to varying degrees. These are  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ , and  $\text{TiO}_2$ . Of these it may be said that the effects of  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  are negligible; other factors being equal, the higher the ratio of  $\text{Al}_2\text{O}_3$  to  $\text{SiO}_2$  the higher will be the softening temperature; the higher the percentage of alkalies, alkaline earths, and iron oxide, the lower will be the softening temperature.

With admitted exceptions, the presence of iron oxide in excess of 20 per cent can be responsible for serious clinker trouble.

Certain special-purpose coals may require the presence or absence of certain mineral components in utilization. The most important of these are calcium oxide, which is a desirable component in the case of the cement industry, and phosphorus and sulphur, which must be kept at a minimum in coking coals destined for the iron and steel industry.

### Friability and Size Stability of Coal

**Friability**, as applied to coal, refers to its tendency to break up or crumble into smaller pieces when subjected to handling; hence a friability index serves to show relative handling properties.

**Size stability** is the opposite of friability and thus indicates the resistance to breakage.

As usually expressed "friability per cent," is the average size of the coal resulting from breakage during test, shown as a percentage of the average size of the lumps taken as a sample. The difference between 100 and the friability per cent is the "size stability per cent."

**Table 2-4. Friability and Size Stability of Various Coals<sup>1</sup>**  
 (Together with "slack" and "abrasion" indexes)

Coal	Friability by tumbler test, per cent		Size stability by drop-shatter test, per cent	
	On 1- to 1- $\frac{1}{4}$ -in. square-mesh lumps	Abrasion (dust) index	On 2- to 3-in. (round-hole) lumps	Slack index
Pennsylvania anthracite . . . . .	19.0	16	93.5	3
Welsh anthracite . . . . .	30.0	17	85.5	8
High-volatile A bituminous (Westmoreland County, Pa.) . . . . .	22.5	14	88.0	6
High-volatile A bituminous (Belmont County, Ohio) . . . . .	28.0	13	80.0	9
High-volatile A bituminous (Minto area, New Brunswick) . . . . .	37.5	18	75.0	13
Medium volatile bituminous (Alta. Mountain Park area) . . . . .	34.0	20	85.0	9
Low-volatile bituminous (Pocahontas lump, W. Va.) . . . . .	40.0	28	78.5	13
Subbituminous B (Alta. Drumheller area) . . . . .	20.0	8	76.5	11
Lignite (Saskatchewan) . . . . .	21.0	7	82.0	8

<sup>1</sup> Condensed from ASTM "Symposium on Significance of Tests of Coal," Philadelphia, June 29, 1937, p. 432.

**Table 2-6. ASTM Suggested Limits for Grouping Coals with Respect to Size Stability<sup>1</sup>**  
 (By drop-shatter test)

**Table 2-5. ASTM Suggested Limits for Grouping Coals with Respect to Friability<sup>1</sup>**

(As tested by 1-hr tumbler test)	
Friability Per Cent	ASTM Suggested Grouping
Below 20	Nonfriable coals, including mainly the hard nonfriable varieties of anthracites
20-30	Medium-friable A coals, including the softer varieties of anthracites, the harder varieties of bituminous, and the tough varieties of subbituminous
30-40	Medium-friable B coals, including the softer varieties of anthracites, and the less hard varieties of medium- and high-volatile bituminous coals
40-50	Friable coals, including mainly the softer varieties of low-, medium-, and high-volatile bituminous coals
Above 50	Very friable coals

<sup>1</sup> From ASTM "Symposium on Significance of Tests of Coal," Philadelphia, June 29, 1937, p. 427.

Size Stability, Per Cent Above 90	
80-90	High-size-stability coals, including mainly the hard nonfriable varieties of anthracite
70-80	Medium-size-stability coals, subgroup A, including the medium-friable anthracites, the more stable low-, medium-, and high-volatile bituminous coals, and the tough varieties of (non-weathered) lower rank subbituminous and lignite coals
Below 70	Low-size-stability coals, including the friable and very friable bituminous and lower rank coals

<sup>1</sup> From ASTM "Symposium on Significance of Tests of Coal," Philadelphia, June 29, 1937, p. 429.

**Methods of testing** as recommended by ASTM include the tumbler test and shatter test, which are essentially as follows:

In the tumbler test carefully sized coal is tumbled in a jar-mill test machine of specified design for 1 hr at 40 rpm. A screen analysis is then made on the tumbled coal and the results reported as

$$\text{Friability per cent} = \frac{100(S - s)}{S}$$

where  $S$  is the average size of the lumps taken as a sample and  $s$  is the average size of the tumbled coal.

If desired a **dust index** may also be reported, representing fines and dust produced in the test, and indicative of the proportion of breakage caused by abrasion.

In the **drop-shatter test** 50 lb of carefully screened coal is dropped twice in a shatter-test machine of standard design, screen analysis obtained, and results reported as

$$\text{Size stability per cent} = \frac{(s) \times 100}{(S)}$$

where  $S$  is the average size of the lumps taken as a sample and  $s$  is the average size of the dropped coal.

**Slack index** is the percentage of the dropped coal passing a  $\frac{3}{4}$ -in. screen. It is indicative of the comparative slack-producing characteristics of the coal being tested.

**Comparative Results of Tumbler and Shatter Tests.** In the tumbler tests, where the lumps fall only short distances and where they continually rub against one another, the breakage caused by abrasion is much more emphasized than in the drop-shatter test, where the lumps drop a distance of 6 ft and where they rub against one another very little. On a given coal, the total breakage is usually more than on a drop-shatter test. The procedure of the latter test, where a 50-lb sample is dropped twice in succession, is considered to produce a breakage effect comparable with that taking place in ordinary commercial handling, whereas the tumbler test serves to indicate the relative weakness of the lumps, such as on repeated handling, as in worm feeders.

**Handling properties** of coal should be shown as an expression of both the size stability and friability values, as

**Handling properties** . . . . . (88-22) or Ss. 88-Fr. 22

where the 88 is the size stability as obtained by a drop-shatter test and 22 is the friability as obtained by a tumbler test.

### MISCELLANEOUS SOLID FUELS

**Torbanite**<sup>1</sup> is a variety of boghead coal. It was named from Torbane Hill, Scotland, where it was mined several years. Torbanite contains a high percentage of volatile constituents, including illuminating and lubricating oils, paraffin, and large quantities of illuminating gases. The heat value is between 14,000 and 18,000 Btu per lb. The origin is probably algae instead of spores. Torbanite is closely related to the bituminous schists and oil shales; it has a dark-brown color; its surface is dull and lusterless; and its fracture is irregular to subconchoidal. The hardness is 2.25 and the specific gravity 1.17 to 1.2. It differs greatly from other coals, for one thing being much higher in hydrogen. Ash content averages about 20 per cent. According to Dana,<sup>2</sup> a typical ash-free analysis is as follows:

	Per Cent
Hydrogen . . . . .	11 48
Carbon .. . . .	81.15
Nitrogen . . . . .	1 37
Oxygen . . . . .	6 00

**Byerite**.<sup>3</sup> This is a term applied by Mallett<sup>4</sup> to a so-called mineral coal somewhat resembling torbanite but differing from it in not cracking in the fire, in being heavier (specific gravity 1.323) and in melting and intumescing (swelling or bubbling) when heated. It gives a large amount of gas and tarry oils, about 30 per cent more than

<sup>1</sup> MOORE, E. S., "Coal," p. 100, John Wiley & Sons, Inc., New York, 1940. Reprinted by permission.

<sup>2</sup> DANA, E. S., "A System of Mineralogy," 6th ed., p. 1022, 1895.

<sup>3</sup> MOORE, E. S., *op. cit.*, p. 101. Reprinted by permission.

<sup>4</sup> MALLETT, E. J., On Middle Park Mineral Coal, *Am. J. Sci.*, vol. 9, p. 146, 1875.

English cannell. The coke is not a true coke but resembles the residue from the distillation of sugar and is too porous and crumbling to support a furnace burden. It is jetblack in color but gives a brown powder which does not color a potash solution brown. It is insoluble in carbon bisulphide, ether, or turpentine.

An analysis is as follows:

	Per Cent
Moisture .....	6.02
Volatile matter <sup>a</sup> .....	39.95
Fixed residue <sup>b</sup> .....	54.03

<sup>a</sup> Gas and tarry oils.

<sup>b</sup> Consists of coke and ash.

**Parrot Coal.** A variety of Scotch cannell coal which produces a marked crackling sound while burning.

**Horn Coal.** A coal from South Wales which, on burning, emits an odor as of burning horn.

**Carbonite.** A natural coke found in England and Virginia. It is a cokelike mineral formed by the baking action of igneous rocks on seams of bituminous coal. It is used as a fuel.

Carbonite is also the name of an activated charcoal made from a mixture of ground anthracite, pitch, and sulphur.

**Albertite** is a solid resembling coal but derived from petroleum. It is found in the province of Mendoza, Argentina.

**Graphite.**<sup>1</sup> Although natural graphites are not in any sense fuels, their formation is so analogous to coal that a brief description seems in order. There are three recognized types of natural graphites: flake, crystalline, and amorphous. It is believed that all graphites are actually crystalline in structure; the difference in appearance and properties lies in the size of the crystals, the method of formation, and the place of occurrence.

*Flake graphite* occurs in scales or lamellae in metamorphic rocks. Each flake is an entity and is surrounded by the rock gangue. It is rather difficult to purify, being very hard to separate from the gangue.

*Crystalline graphites* are pure, and since the best varieties that come from Ceylon and Madagascar occur in veins or pockets, it is only a question of proper selection to obtain graphite with low ash and high purity. These graphites, however, like all carbon material, have an infinite variety of minute differences in quality.

*Amorphous graphite* is considered to be composed of minute graphite crystals. When ground to fine flours it has a dull black appearance totally unlike the lustrous appearance of the ground flake or crystalline graphites. Amorphous graphites from Sonora, Mexico, constitute the supply available for the United States.

Table 2-7. Analyses of Various Natural Graphites<sup>1</sup>

Origin	Ash	Volatile	Carbon	Sp gr
Ceylon .....	0.05	0.16	99.79	2.570
Ticonderoga....	0.28	0.90	98.82	2.246
Mexico (Sonora)	2.15	1.19	96.66	2.170
Madagascar....	1.76	0.82	97.42	

<sup>1</sup> MANTELL, C. L., "Industrial Carbon," 2d ed., D. Van Nostrand Company, Inc., New York, 1946.

<sup>1</sup> MANTELL, C. L., "Industrial Carbon," 2d ed., pp. 223-224, D. Van Nostrand Company, Inc., New York, 1946.



## CHAPTER 3

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### PENNSYLVANIA ANTHRACITE AND OTHER ANTHRACITIC COALS

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## **. ANTHRACITE**

Anthracite is defined as a hard compact variety of natural coal of high luster. It differs from bituminous coal in containing only a small amount of volatile matter, in consequence of which it burns with a nearly nonluminous flame.

**Analytical Boundaries.** By the now universally accepted coal classification of the ASTM, true anthracite, as distinguished from meta-anthracite above and semianthracite below, has the following **analytical limits**:<sup>1</sup>

**ASTM Definition** (mineral-matter-, moisture-free basis). Dry fixed carbon 92 per cent or more and less than 98 per cent. Dry volatile matter 8 per cent or less and more than 2 per cent. Nonagglomerating.

**Location of Anthracite.** Large quantities of true anthracite are found and commercially mined in several countries, such as China, Russia, Indo-China, Wales, and Ireland (see Reserves, page 13). Statistics of the U.S. Bureau of Mines show that, of an estimated world production in 1946 of 118 million metric tons, the United States produced 55 million, or 47 per cent (Table 3-1). Of the latter amount, all but about 50,000 annual tons commercially produced is mined in Pennsylvania (see Anthracitic Coals section for a discussion of United States anthracites other than those of Pennsylvania).

### **PENNSYLVANIA ANTHRACITE<sup>2</sup>**

#### **LOCATION OF FIELDS<sup>3</sup>**

In 1749, the Proprietary Government of Pennsylvania purchased from the Indians of the Six Nations, a section of land about 125 miles long by 35 miles wide, for the sum of 500 pounds, or about \$2,500. This section comprised practically all the anthracite fields of Pennsylvania.

The **total area** containing workable beds of anthracite is only **484 sq miles** in extent, or about one thousand times smaller than the area of the bituminous coal fields of the United States. It is divided geographically into four distinct canoe-shaped fields, all having their greatest length in a northeasterly to southwesterly direction. Although separated, these fields are adjacent, all lying in the northeastern part of the state and within the 10 **counties** of Wayne, Susquehanna, Lackawanna, Luzerne, Carbon, Schuylkill, Columbia, Northumberland, Dauphin, and Lebanon.

For trade purposes, these fields are divided into three **regions**, the **Wyoming**, **Lehigh**, and **Schuylkill** regions. The Wyoming region comprises the northern field. The Lehigh region embraces the eastern middle field. The Schuylkill region includes the western middle and southern fields.

#### **MINING AND RECOVERY METHODS**

**Description of Fields.** Cross sections of all the anthracite fields show up to some 14 roughly parallel veins ranging in thickness from a few inches to one, the Mammoth, which at one point reaches a maximum of 290 ft. In all basins, the lowest vein slopes upward from its lowest point underground, at pitches ranging from a few degrees to almost vertical, until ground level is reached where, with a usual coverage of only relatively small amounts of debris, the vein terminates as "outcroppings" at each

<sup>1</sup> See Table 2-1 for a full table of ASTM coal classifications from meta-anthracite through lignite.

<sup>2</sup> For anthracites from Rhode Island, New Mexico, and Colorado, see Anthracitic Coals, p. 74.

<sup>3</sup> "The Story of Anthracite," Hudson Coal Co., Scranton, Pa., 1932.

Table 3-1. World Production of Anthracite, 1939-1946<sup>1</sup>  
(In metric tons)

Country <sup>a</sup>	1939	1940	1941	1942	1943	1944	1945	1946
China <sup>b</sup> .....	3,633,365	5,448,464	6,532,402	7,320,664	°	°	1,451,000	757,114
Eire.....	90,455	74,170	104,871	116,290	123,387	130,198	123,468	°
France.....	9,291,000	8,036,000	8,747,000	8,963,000	8,205,000	4,964,000	°	°
Indo-China, French.....	2,534,400	2,414,200	2,251,000	1,159,000	955,000	489,700 <sup>d</sup>	218,000 <sup>d</sup>	°
Italy.....	107,255	162,140	158,339	163,565	122,075	°	53,446	°
Korea (Chosen).....	2,233,864	3,153,175	3,519,385	3,898,282	4,157,101	4,530,262	°	104,989
Morocco, French.....	115,600	143,500	139,050	119,400	102,290	134,400	178,600	1,130,000 <sup>d</sup>
Peru.....	3,514	4,500	4,600	5,000	22,716	14,545	36,848	221,750
Portugal.....	294,081	286,854	436,324	404,144	368,321	389,638	436,117	82,089
Rumania.....	4,400	13,724	13,533	5,125	8,071	2,590	5,000 <sup>d</sup>	°
Spain.....	563,963	1,095,875	1,148,332	1,242,932	1,151,763	1,516,035	1,529,532	1,522,188
Switzerland.....	2,500	7,000 <sup>d</sup>	42,385	108,096	104,150	51,232	°	°
United Kingdom.....	6,163,406	5,687,330	4,401,448	4,351,327	4,196,671	3,652,881	3,213,405	3,582,084
United States.....	46,708,319	46,705,836	51,136,164	54,728,109	55,014,679	57,788,602	49,834,944	54,890,625
Total (estimate).....	119,096,000	122,638,000	128,006,000	116,922,000	117,901,000	114,039,000	105,270,000	118,168,000

<sup>1</sup> Compiled by P. Roberts, "Minerals Yearbook," p. 42, U.S. Bureau of Mines, Anthracite Preprint, 1946.<sup>a</sup> In addition to countries listed, Belgium, Bulgaria, Germany, Japan, U.S.S.R., but data are not available.<sup>b</sup> Excludes Kwangtung Peninsula.<sup>c</sup> Data not available, but author's estimate is included in totals, as is estimate of countries in note <sup>a</sup>.<sup>d</sup> Estimate.

**Table 3-2. Physical Properties of Pennsylvania Anthracite<sup>1</sup>**

Luster.....	Vitreous to submetallic
Structure.....	Laminated to amorphous. Laminae obscure because of uniformity of luster
Fracture.....	Conchoidal to rectangular. Chiefly conchoidal
Streak.....	Dark brown to black, chiefly black
Hardness.....	2.75-3.00 (the term hardness is used herein as a measure of resistance to abrasion)
Friability.....	23-51 per cent friable

<sup>1</sup> *Trans. AIME Coal Div.*, vol. 108, p. 332, 1934.

veins that comprise the area's deep mining, there should be no material difference in the characteristics of the coal unless it has been unduly weathered or broken because of proximity to the surface.

**Table 3-3. The Anthracite Fields of Pennsylvania**

Region	Field	Counties included <sup>a</sup>	Area, sq miles	Per cent industry production <sup>b</sup>
Wyoming	Northern	Luzerne, Lackawanna, Wayne, Susquehanna	176	45 0
Lehigh	Eastern middle	Luzerne, Carbon, Schuylkill, Columbia	33	8.8
Schuylkill	Western middle	Northumberland, Schuylkill, Columbia	94	23 1
	Southern	Schuylkill, Carbon, Dauphin, Lebanon	181	23 1
Totals . . . . .			484	100 0

<sup>a</sup> Counties shown in *italics* comprise relatively minor percentages of the field areas.<sup>b</sup> Based upon total 1946 breaker, washery, and dredge production, U.S. Bureau of Mines.

**Deep mines**, which in 1946 accounted for 63 per cent of production, employ vertical shafts, inclined slopes, or horizontal tunnels as a means of access to underlying veins of coal. In most cases, particularly where the mine is of any size, more than one vein will be reached by the same shaft, slope, or tunnel; and in addition the same breaker often cleans and sizes the output of more than one such mine. Thus, even though there is often a considerable difference in the analyses and burning characteristics of adjacent veins, these differences, even if known, can seldom be used to consumer advantage or traced to the commercial analyses, because the production of virtually all deep mines is in reality a blend of veins and parts of veins.

**Recovery of previously rejected coal**, from culm and silt banks, accounted for a further 14 per cent of the industry's 1946 production. Principal sources are defined as follows:

**A rock bank** is the refuse from a modern wet breaker. These rock banks contain from 1 to 5 per cent of marketable coal and are of no value except for filling.

**A culm bank** is an accumulation of rock, bone, and coal from an old dry breaker. These banks vary greatly in quality and in size. As of 1928, it was reported<sup>1</sup> that there were over 92 million tons of material in culm banks of which the coal ranged from 20 to 60 per cent for the newer banks to 80 per cent for the older banks. Since that date, a considerable amount of this coal has been reclaimed and not replaced by modern methods; however, this is the last comprehensive survey available.

**A silt bank** is an accumulation of fine-sized coal, bone, and slate which is settled out of breaker water. This material is known also as sludge, fines, slush, and mud. As found,

<sup>1</sup> "Anthracite Culm and Silt," *Pennsylvania Geological Survey Bull.* M-12, Harrisburg, Pa., 1928.

this silt usually contains from 15 to 50 per cent ash, which can be prepared to as low as 10 to 12 per cent coal by the rejection of 15 to 60 per cent of the raw material as refuse.

Unfortunately no modern survey of culm and silt is available, the latest being that in "Anthracite Culm and Silt," *Pennsylvania Geological Survey Bulletin M-12*, dated 1928. Obviously this includes much material that has since been reclaimed, particularly since the entire Second World War period has intervened. Nevertheless, their reported quantities are shown in Table 3-4 as being the best available data.

**Table 3-4. Quantity of Anthracite Culm and Silt in Banks<sup>1</sup>**  
(In long tons of 2,240 lb)

Field	Culm	Silt	Mixed	Total
Northern .....	8,125,000	8,035,000	30,355,000	17,955,000
Southern .....	37,745,000	36,815,000	10,000,000	84,560,000
Western middle.....	43,785,000	40,735,000	17,175,000	101,695,000
Eastern middle.....	2,430,000	6,200,000	1,385,000	10,015,000
Total .....	92,085,000	91,785,000	30,355,000	214,225,000

<sup>1</sup> These tonnages are not recoverable marketable coal. The material composing these banks ranges from 20 to 80 per cent marketable coal.

**Table 3-5. 1946 Production of Pennsylvania Anthracite<sup>1</sup>**

Source	Net tons	Per cent of total
Deep mining .....	38,021,943	61.8
Mechanically loaded <sup>a</sup> .....	(15,619,162)	(25.4)
Hand loaded <sup>a</sup> .....	(22,402,781)	(36.4)
Strippings.....	12,836,842	20.9
Reclamation from banks .....	8,408,605	13.7
River coal .....	1,132,394	1.8
"Bootleg" <sup>b</sup> .....	1,096,417	1.8
Total .....	61,496,201	100.0

<sup>1</sup> "Manual of Statistical Information," Anthracite Institute, 1947.

<sup>a</sup> Subtotals of Deep mining given in parentheses.

<sup>b</sup> Estimated.

### ANTHRACITE SPECIFICATIONS

Two sets of specifications are in use in the Pennsylvania anthracite industry. Those shown in Table 3-6 are the sizing and quality standards adopted voluntarily for the optional guidance of the industry by the Anthracite Committee, representing anthracite-producing companies. The specifications shown in Table 3-7 are those provided by the Pennsylvania Legislature House Bill 1050, effective Sept. 1, 1947, and mandatory after Sept. 1, 1949. After the latter date, all Pennsylvania anthracite labeled "Standard Anthracite" must conform to these standards as to undersize and ash or slate and bone content.

It will be noted that, within the scope of the Pennsylvania state specifications which do not go below the rice size, the two codes are identical except that the state has omitted specifications for minimum undersize and maximum oversize.

### ANALYSES OF PENNSYLVANIA ANTHRACITES

**Range of Analyses.** The principal differences in the analyses from different parts of the relatively compact Pennsylvania anthracite field are in the volatile and ash contents. The two are not interrelated because the variation in ash in anthracite as marketed is due almost entirely to thoroughness of preparation rather than to inherent ash in the coal.

Table 3-6. Anthracite Specifications<sup>1</sup>

Size of coal	Test mesh, round, in.		Oversize, max per cent	Undersize, per cent		Max impurities, per cent		
	Through	Over		max	min	Slate <sup>a</sup>	Bone <sup>a</sup>	Ash <sup>b</sup>
Broken.....	4 $\frac{3}{8}$	3 $\frac{1}{4}$ -3		15	7 $\frac{1}{2}$	1 $\frac{1}{2}$	2 or	11
Egg.....	3 $\frac{1}{4}$ -3	2 $\frac{7}{16}$	5	15	7 $\frac{1}{2}$	1 $\frac{1}{2}$	2 or	11
Stove.....	2 $\frac{7}{16}$	1 $\frac{5}{8}$	7 $\frac{1}{2}$	15	7 $\frac{1}{2}$	2	3 or	11
Nut.....	1 $\frac{5}{8}$	1 $\frac{3}{16}$	7 $\frac{1}{2}$	15	7 $\frac{1}{2}$	3	4 or	11
Pea.....	1 $\frac{3}{16}$	$\frac{9}{16}$	10	15	7 $\frac{1}{2}$	4	5 or	12
Buckwheat....	$\frac{9}{16}$	$\frac{5}{16}$	10	15	7 $\frac{1}{2}$			13
Rice.....	$\frac{9}{16}$	$\frac{5}{16}$	10	17	7 $\frac{1}{2}$			13
Barley.....	$\frac{5}{16}$	$\frac{3}{32}$	10	20	10			15
No. 4.....	$\frac{3}{32}$	$\frac{3}{64}$	20	30	10			15
No. 5.....	$\frac{3}{64}$	.....	30	No limit				16

<sup>1</sup> Approved and adopted by the Anthracite Committee, effective July 28, 1947.

<sup>a</sup> When slate content in the sizes from broken to nut, inclusive, is less than above standards, bone content may be increased by one and one-half times the decrease in the slate content under the allowable limits, but slate content specified above shall not be exceeded in any event.

<sup>b</sup> Ash determinations are on a dry basis.

A tolerance of 1 per cent is allowed on the maximum percentage of undersize and the maximum percentage of ash content. The maximum percentage of undersize is applicable only to anthracite as it is produced at the preparation plant. "Slate" is defined as any material which has less than 40 per cent of fixed carbon. "Bone" is defined as any material which has 40 per cent or more, but less than 75 per cent of fixed carbon.

Table 3-7. Standard Anthracite<sup>1</sup>

Size of anthracite	Test mesh, round, in.		Undersize, <sup>a</sup> max, per cent	Ash content, <sup>b</sup> max, per cent		Max slate, <sup>c</sup> per cent	Bone <sup>d</sup>
	Through	Over					
Broken. ....	4 $\frac{3}{8}$	3 $\frac{1}{4}$ -3	15	11	or	1 $\frac{1}{2}$	2
Egg.....	3 $\frac{1}{4}$ -3	2 $\frac{7}{16}$	15	11	or	1 $\frac{1}{2}$	2
Stove.....	2 $\frac{7}{16}$	1 $\frac{5}{8}$	15	11	or	2	3
Nut.....	1 $\frac{5}{8}$	1 $\frac{3}{16}$	15	11	or	3	4
Pea.....	1 $\frac{3}{16}$	$\frac{9}{16}$	15	12	or	4	5
Buckwheat....	$\frac{9}{16}$	$\frac{5}{16}$	15	13			
Rice.....	$\frac{9}{16}$	$\frac{5}{16}$	17	13			

<sup>1</sup> As defined by Pennsylvania House Bill No. 1050, May 7, 1947, effective Sept. 1, 1947.

<sup>a</sup> As to the maximum percentage of undersize and the maximum percentage of ash content, a tolerance of 1 per cent shall be allowed when slate content in the sizes from broken to nut, inclusive, is less than above standards. Bone content may be increased by one and one-half times the decrease in the slate content under the allowable limits, but slate content specified above shall not be exceeded in any event. The maximum percentage of undersize shall be applicable only to anthracite as it is produced at the preparation plant. Anthracite which conforms to the sizing herein fixed and conforms also to either the specification for ash content or the specification for slate and bone content shall be deemed to be "Standard Anthracite."

<sup>b</sup> Ash content. The percentage which the weight of the ash from anthracite resulting from burning bears to the weight of the anthracite before burning after the anthracite has been dried for 1 hr at 105°C.

<sup>c</sup> Slate. Any material which has less than 40 per cent of fixed carbon.

<sup>d</sup> Bone. Any material which has 40 per cent or more but less than 75 per cent of fixed carbon.

**Volatile-matter Content.** Turner plotted definite isovolatilic curves for the entire anthracite region (Fig. 3-1) which proved to be sufficiently accurate for most practical purposes. He also showed that lines of equal specific gravity paralleled the isovolatilic curves with the approximate relationship shown in Fig. 3-2. Volatile is an important determination in anthracite, as it serves as a rough guide to the burning characteristics of the coal.

**Burning Characteristics.** In general, anthracites with low volatile content have higher ignition temperatures and are slower burning with equal draft intensities than coals of higher volatile. In the trade, reference to **slow-burning**, **medium-burning**, and **free-burning** anthracite usually parallels low-, medium-, and high-volatile groupings. Although strong local preferences are frequently shown for coal of one type or

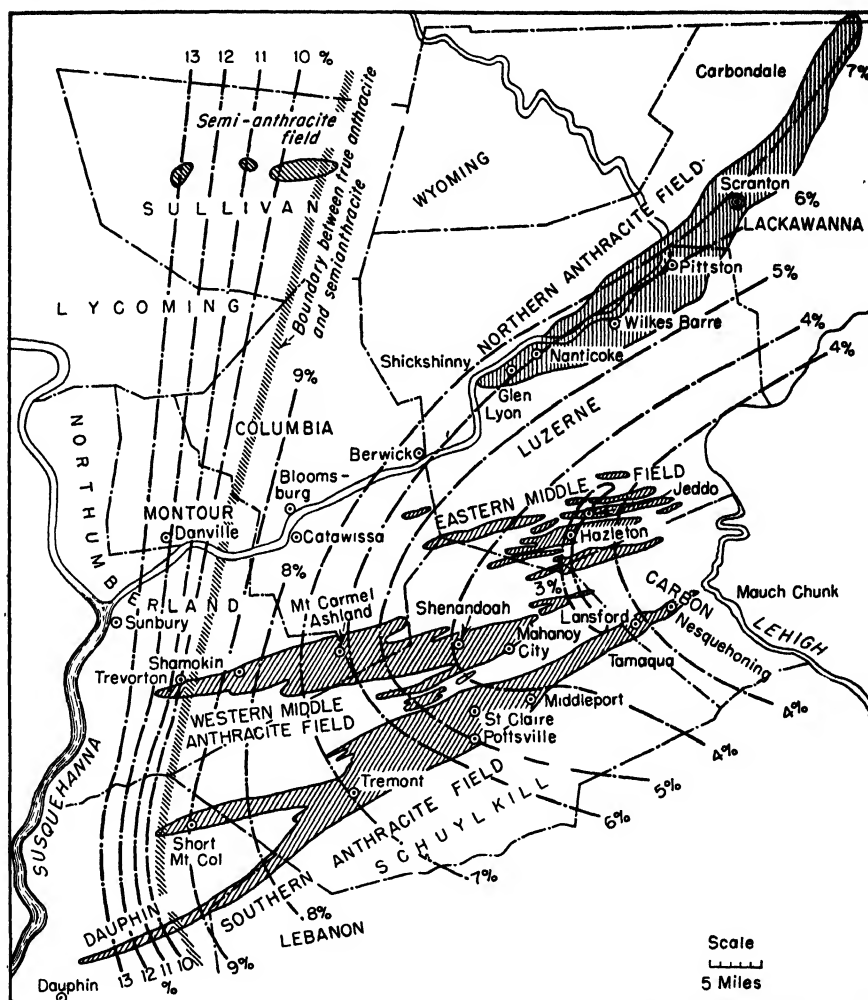


FIG. 3-1. Map of the anthracite region showing isovolatile contours. [Note: Volatile, per cent (moisture- and mineral-matter-free basis).]

the other, the actual difference in combustibility of any equally sized and prepared anthracites is not over 10 per cent on either side of the mean. In hand firing, this difference can be compensated by suitable draft-damper adjustments. Similarly, in most mechanical-firing equipment, adjustments will usually equalize any such differences in combustion rate. A notable exception is that of underfeed domestic stokers, where flexibility of design is sometimes inadequate to cope with the higher ignition

"hard-burning" coals and where the type of ash removal is not sufficiently positive to handle clinker from the extremely free-burning types, such as Lykens. A further factor for consideration is that stokers of the worm- or plunger-feed type meter the coal fed by volume rather than by weight. Thus, with the dense low-volatile coals, more pounds will usually be fed per hour for the same feed ratio.

**Ash Content.** High ash content is a disadvantage from at least two angles, aside from any that enter into combustion. (1) It proportionately reduces the quantity of the coal components available for producing heat, with the effect of higher freight

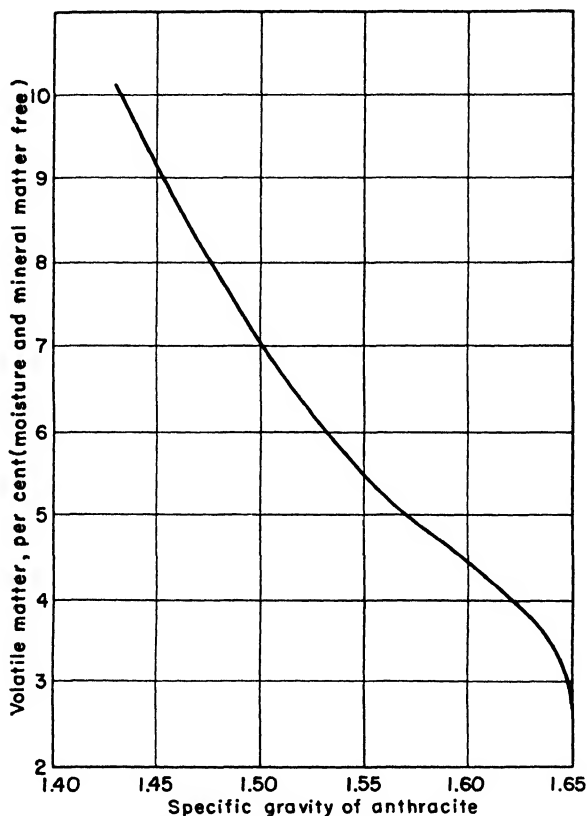


FIG. 3-2. Approximate ratio between volatile and specific gravity (for Pennsylvania anthracite).

rates and costs per pound of combustible; and (2) it increases the cost and difficulty of ash disposal. Two coals purchased on a basis of equal heat content or equal cost per unit of heat, but with different ash contents, will be equal from the angle of item 1, but the lower ash coal will still be the more valuable to the amount of the lesser cost and difficulty of disposing of the ash. (Where there is a market for ash, this position might be neutralized or, depending on ash revenue, even reversed.)

**Ash-fusion Temperatures.** Most anthracites have ash-softening temperatures sufficiently high to avoid troublesome clinker with properly designed and properly operated equipment. An exception is the coal from the western extremities of the Dauphin County fishtails (see map, Fig. 3-1), where softening temperatures as low as

**Table 3-8. Average Analyses of Anthracite Samples<sup>1</sup>**  
(Collected by the Bureau of Mines in Cooperation with the Anthracite Institute)

Lehigh Region							
Coleraine, Gowen, Cranberry, Hazelton Shaft, and Spring Mountain Collieries							
Size . . . . .	Egg	Stove	Chestnut	Pea	Buck- wheat	Rice	Barley
Total tonnage (yearly pro- duction)	116,401	508,576	601,906	276,323	310,353	158,682	158,939
Moisture "as received," per cent	4.6	5.0	5.2	6.4	6.1	6.2	6.9
Volatile matter "dry coal," per cent	2.9	2.8	2.8	3.3	3.5	3.5	3.7
Fixed carbon "dry coal," per cent	88.0	88.1	87.9	86.4	85.8	84.0	83.7
Ash "dry coal," per cent	9.1	9.1	9.3	10.3	10.7	12.5	12.6
Sulphur "dry coal," per cent	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Btu "as received," . . .	12,820	12,810	12,730	12,430	12,390	12,080	11,990
Btu "dry coal" . . .	13,440	13,480	13,430	13,280	13,190	12,880	12,880
Btu "moisture- and ash- free" . . .	14,790	14,830	14,810	14,800	14,770	14,720	14,740
Softening temperature of ash, deg F <sup>a</sup> . . .	2910	2920	2910	2820	2790	2910	2830

Schuylkill Region							
East Bear Ridge, St. Clair, William Penn, Pennsylvania, Lyle, Oak Hill Packer No. 5, Enterprise, Coaldale, Lansford, and Alliance Collieries							
Size . . . . .	Egg	Stove	Chestnut	Pea	Buck- wheat	Rice	Barley
Total tonnage (yearly pro- duction)	355,073	1,029,315	1,309,236	664,961	826,967	370,580	543,360
Moisture "as received," per cent	4.2	4.1	4.5	5.8	5.6	5.7	7.9
Volatile matter "dry coal," per cent	4.1	4.1	4.1	4.0	4.5	3.8	4.1
Fixed carbon "dry coal," per cent	86.4	86.5	85.9	84.3	83.0	82.7	82.1
Ash "dry coal," per cent	9.5	9.4	10.0	11.7	12.5	13.5	13.8
Sulphur "dry coal," per cent	0.7	0.7	0.6	0.6	0.7	0.6	0.6
Btu "as received," . . .	12,980	12,990	12,830	12,360	12,290	12,070	11,770
Btu "dry coal" . . .	13,550	13,550	13,430	13,120	13,020	12,800	12,780
Btu "moisture- and ash- free" . . .	14,970	14,960	14,920	14,860	14,880	14,800	14,830
Softening temperature of ash, deg F <sup>b</sup> . . .	2840	2840	2840	2870	2870	2880	2880

Wyoming Region							
Pine Brook, Richmond Shaft, Price Pancost, Harry Taylor, Rush Brook, Legitts Creek, Van Storeh, Johnson Shaft and Slope, Wingfoot Slope, Capouse Shaft and Slope, Raymond, Ontario, Blue Ridge Tunnel, Pittston Nos. 1 and 5, Underwood, Ewen, Butler (Pittston No. 9), Olyphant, Marvine, Pompey (formerly Winton), Powderly, Gravity Slope, Kingston No. 4, Wanamie, Maxwell, Loomis, Alden, Susquehanna No. 6, Susquehanna No. 7, Pine Ridge, Delaware, Laurel Run, Dorrance, Prospect Shaft, Midvale Slope, Henry Shaft, Westmoreland, Harry E. Lance, Gray Slope, No. 2 Shaft, and Clifford Slope Collieries							
Size . . . . .	Egg	Stove	Chestnut	Pea	Buck- wheat	Rice	Barley
Total tonnage (yearly pro- duction)	1,641,752	4,258,270	4,858,358	2,063,006	2,578,842	1,195,101	974,854
Moisture "as received," per cent	4.2	4.3	4.8	6.3	6.1	5.7	6.8
Volatile matter "dry coal," per cent	4.6	4.6	4.6	4.5	4.7	4.8	4.7
Fixed carbon "dry coal," per cent	86.3	86.1	85.7	84.2	83.7	83.1	81.6
Ash "dry coal," per cent	9.1	9.3	9.7	11.3	11.6	12.1	13.7
Sulphur "dry coal," per cent	0.7	0.7	0.7	0.7	0.7	0.7	0.8
Btu "as received," . . .	13,130	13,080	12,950	12,500	12,480	12,450	12,070
Btu "dry coal" . . .	13,710	13,670	13,600	13,340	13,290	13,200	12,950
Btu "moisture- and ash- free" . . .	15,080	15,070	15,060	15,040	15,030	15,020	15,010
Softening temperature of ash, deg F <sup>c</sup> . . .	2890	2890	2900	2900	2900	2910	2900

<sup>1</sup> U.S. Bur. Mines Repts. Invest. 3283.

<sup>a</sup> Softening temperatures of ash given are averages of determinations which include numerous "plus maximum readings" which vary between 2520 and 2919 in this region.

<sup>b</sup> Softening temperatures of ash given are averages of determinations which include numerous "plus maximum readings" which vary between 2490 and 2919 in this region.

<sup>c</sup> Softening temperatures of ash given are averages of determinations which include numerous "plus maximum readings" which vary between 2660 and 2970 in this region.



Table 3-9. Weighted Average Analyses of Pennsylvania Anthracite<sup>1</sup>

Size.....	Egg	Stove	Chestnut	Pea	Buck- wheat	Rice	Barley
Total tonnage (yearly production)....	2,113,226	5,796,161	6,769,500	3,004,290	3,716,162	1,724,383	1,677,153
Moisture "as received," per cent. . . . .	4 2	4 3	4 8	6 2	6 0	5 7	7 2
Volatile "dry coal," per cent. . . . .	4 4	4 4	4 3	4 3	4 6	4 5	4 4
Fixed "dry coal," per cent. . . . .	86 4	86 3	86 0	84 4	83 7	83 1	82 0
Ash "dry coal," per cent	9 2	9 3	9 7	11 3	11 7	12 4	13 6
Sulphur "dry coal," per cent . . . . .	0 7	0 7	0 7	0 7	0 7	0 7	0 7
Btu "as received" . . . .	13,100	13,040	12,900	12,470	12,430	12,330	11,960
Btu "dry coal" . . . . .	13,670	13,630	13,550	13,290	13,220	13,080	12,890
Btu "moisture- and ash- free" . . . . .	15,060	15,030	15,010	14,980	14,970	14,930	14,920
Softening temperature of ash, deg F . . . . .	2890	2890	2890	2890	2880	2900	2880

<sup>1</sup> U.S. Bur. Mines Repts. Invest. 3283. These samples were taken as the coal came from the breakers immediately after washing. Therefore, "Moisture as received" includes, in addition to inherent moisture of about 2 per cent, the moisture due to water clinging to the coal from the washing process. In a short time after loading, much of the free moisture drains off so that coal delivered to the consumer would have a heating value, according to size, between 175 and 350 Btu per lb higher than shown in the column "Btu as received."

Table 3-10. Weighted Average Analyses of Fine-sized Anthracite

(As reported by 53 companies representing approximately 80 per cent of the 1943 production)

	No. 4 buckwheat	No. 5 buckwheat
Sizing:		
Standard	$\frac{3}{16} \times \frac{3}{16}$	$\frac{3}{16} \times 0$
Deviation (by 13 per cent of industry)	$\frac{3}{16} \times \frac{1}{16}$	
Undersize, max per cent	22 1	30 2
Min per cent	12 8	16 8
Oversize, max per cent . . . .	18 7	17 4
Min per cent . . . . .	9 6	10 9
Ash content:		
Max ash content, per cent . . .	15 4	15 9
Min ash content, per cent . . .	10 8	9 7
Btu content. . . . .	12,904	13,064
Fusion point of ash, deg F . . . .	2811	2885
Range of Analyses Reported for Fine-sized Anthracite		
Ash content, max. . . . .	11 6-20 3	12 0-24 0
Min . . . . .	7 2-17 0	9 0-20 0
Btu . . . . .	11,000-13,600	12,500-13,500
Fusion point of ash, deg F . . . .	2300-3000	2740-3000

Table 3-11. Analysis of No. 5 Buckwheat from Flotation Process, Typical Size and Ash Tests<sup>1</sup>

	Per Cent		Per Cent
Sizing on 10 mesh.....	0 1	Sizing on 65 mesh . . . . .	14 3
Sizing on 14 mesh . . . . .	0 1	Sizing on 100 mesh . . . . .	19 0
Sizing on 20 mesh . . . . .	2 2	Sizing on 150 mesh . . . . .	14 8
Sizing on 28 mesh . . . . .	5 0	Sizing on 200 mesh . . . . .	10 3
Sizing on 35 mesh . . . . .	9 3	Through 200 mesh. . . . .	12 4
Sizing on 48 mesh. . . . .	12 6	Ash (dry basis) . . . . .	12 6

<sup>1</sup> Lehigh Navigation, Tamaqua Colliery, 1947, average of three tests.

**Table 3-12. Average Ultimate Analyses of Face Samples of Pennsylvania Anthracite by Fields<sup>1</sup>**  
(Moisture- and ash-free basis)

Field	H <sub>2</sub>	C	N <sub>2</sub>	O <sub>2</sub>	S	Btu
Northern.....	2.8	92.4	1 1	2.5	1.2	15,038
Eastern middle.....	2.1	94.7	0.8	1 6	0.8	14,828
Western middle, Shamokin district	3 6	91.2	1.5	2 6	1.1	14,258
Western middle, West Mahanoy district	2.3	94.3	0 9	1 5	1 1	14,867
Southern:						
Panther Creek district...	2 1	95 0	0 8	1 4	0.7	14,823
East Schuylkill district...	2.0	94 8	0 8	1 7	0.7	14,802
West Schuylkill district...	2.0	94 8	0 8	1 7	0.7	14,898
Lykens district...	3.3	92 0	1 3	2 6	0 8	15,237
Southern fishtail <sup>a</sup> ...	3 4	93.6	1 1	1 1	0 8	15,580
Shamokin district, <sup>b</sup> max volatile...	3.7	91.3	1 5	2 6	0.9	15,270
Lykens district, <sup>b</sup> max volatile...	3 1	92 5	1 1	2 7	0 6	15,100
Avg .....	2 5	93.7	1 0	2 0	0.9	14,968

<sup>1</sup> *Trans. AIME Coal Div.*, vol. 108, p. 332, 1934.

<sup>a</sup> Not included in averages.

<sup>b</sup> Gold mine run.

**Table 3-13. Analysis of Volatile Matter in Various Anthracites<sup>1</sup>**

	Dry coal analyses								Volatile		Gas analyses						Sources
	Gram	V.M.	H <sub>2</sub>	C	N <sub>2</sub>	O <sub>2</sub>	S	Ash	Gram H <sub>2</sub> O	Gas cc	CO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>	CO	CH <sub>4</sub>	
Low volatile ..	44.5	3.8	2.0	85.6	0.8	1.4	0 6	9 6	0 4	7,003	1 8	2 3	3 83	2 4	8 4	2 3 7	1
Medium volatile ..	42 9	5 6	2 6	83 3	0 9	2 1	1 2	9 9	1 0	8,495	2 0	1 1	84.2	2 6	4 1	6 0	1
High volatile.	42 0	7 6	2 9	82 6	1 1	2.5	0 7	10 2	0.6	9,518	2.2	1.0	83 6	2.0	4.1	7.1	1
Northern field	43 0	5 5	2 5	..	0 9	2.2	...	...	1 0	8,360	1.8	1.0	85.2	1.8	4.1	6.0	2
Southern field	44 6	5 6	2 4	..	0.9	1.8	...	...	0 5	8,005	2.1	1.2	83.3	3.8	4.0	5.6	2
Eastern middle	44 8	3 2	1 9	...	0 7	1 6	...	...	0 2	6,375	1.9	2 6	81.1	6.9	5.5	1.9	2
Western middle	44 3	4 7	2 1	...	0 7	1.5	...	...	0 4	7,363	1.8	3.3	78 8	7.4	4 5	4 1	2

NOTES: The appearance of small quantities of hydrogen sulphide in every case. No illuminants were noted in any of the gas samples; no tar was emitted by any of the samples. The gas is largely hydrogen, averaging 4,500 cu ft of gas under standard conditions per ton of anthracite.

<sup>1</sup> Volatile Matter of Pennsylvania Anthracite, *Ind. Eng. Chem.*, vol. 27, p. 1373, November, 1935.

<sup>2</sup> Composition of Volatile Matter in Pennsylvania Anthracite, *Anthracite Institute Laboratory Rept.* 3002, May 10, 1934.

**Table 3-14. Analysis of Anthracite Ashes<sup>1</sup>**  
(In per cent)

	Pennsylvania			Welsh	Scotch	Russian
	Range <sup>1</sup>	Coal ash <sup>2</sup>	Slate ash <sup>2</sup>			
SiO <sub>2</sub> .....	51-69	69 00	61.60	35.4	54.4	26.9
Al <sub>2</sub> O <sub>3</sub> .....	26-39	26 46	32.17	38.2	29.7	36.9
Fe <sub>2</sub> O <sub>3</sub> .....	2-11	3.24	3.70	19.3	9 9	28.9
CaO .....	0 3-1 4	0 40	0 40	5.8	6 0	4 4
MgO .....	0-0 8	0 20	0.20	1 5	..	1.3
Alkalies. ....	0 4-2 2	0 70	1.93	0.7	..	1.5

<sup>1</sup> JONES and BULLER, *Ind. Eng. Chem. Anal. Ed.*, vol. 8, p. 25, 1936.

<sup>2</sup> Northern Field (Scranton) Coal, *Ind. Eng. Chem.*, vol. 27, p. 953, 1935.

2100°F are reported. However, these coals are sufficiently high in volatile to be near if not actually semianthracites, even if not generally classified as such by the trade.

**General Ash-softening Characteristics.** The ash-softening temperatures for anthracite coals from the northern, eastern middle, and western middle fields and the western half of the southern field are in Class I, the refractory group, with softening temperatures above 2600°F. Anthracite from the western half of the southern field shows ash-softening temperatures in the Class II, or medium-fusibility, group, with softening temperatures generally between 2200 and 2600°F.

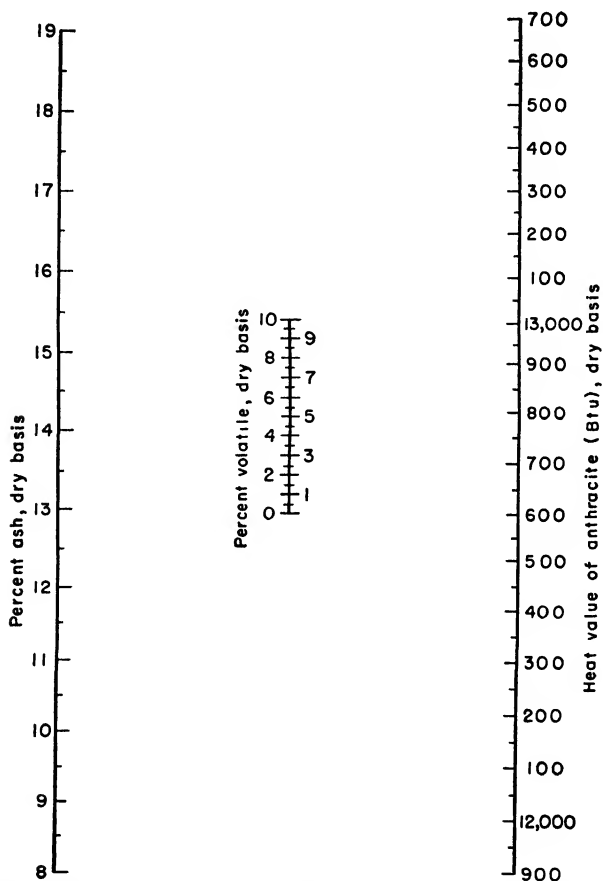


FIG. 3-3. Chart for estimating Btu of anthracites from proximate analysis.

#### GENERAL APPLICATION OF THE SIZES OF ANTHRACITE

**Egg**, the largest size generally marketed for domestic purposes, should be used in furnaces having a diameter or width of not less than 24 in. and a depth of at least 16 in. The firing of this size in smaller furnaces often results in unnecessary ashpit losses.

**Stove** is generally suitable where the firepot is not less than 16 in. wide and 12 in. deep.

**Chestnut** is suitable for furnaces 10 to 16 in. deep and up to 20 in. in diameter. It is also suitable for many types of kitchen ranges and service water heaters.

**Pea** frequently can be used to advantage where the boiler or furnace is considerably larger than necessary. It can also be used in mild weather for banking. In substituting pea for the larger sizes, care must be exercised in shaking the grates, and adequate draft must be available. Pea is also used for service water heaters and kitchen ranges. Pea is the smallest size that can be used with natural draft under normal conditions (domestic).

**No. 1 buckwheat** is mostly used in magazine feed boilers, mechanical stokers, and with forced-draft blowers. Its use with natural draft requires a chimney height of at least 50 ft.

**No. 2 buckwheat, or rice,** is used on some domestic stokers. Depending upon design, the rating of the same will range from equal to 10 per cent below operation on No. 1 buckwheat. Rice is also a popular size in small hand-fired commercial plants with forced draft for combustion.

**No. 3 buckwheat, or barley,** is used extensively in manufacturing and large steam plants. It is usually burned on traveling-grate stokers (see Chap. 23 for further details). Considerable barley is hand-fired with forced-draft systems in the smaller and medium-sized plants.

**No. 4 buckwheat** is used in traveling-grate stokers, mixed with bituminous coal, pulverized, briquetted, etc.

**No. 5 buckwheat** is principally used for pulverization.

#### Additional Uses for Steam-size Anthracite<sup>1</sup>

1. No. 1 buckwheat
  - a. Domestic hand-fired and stoker-fired
  - b. Industrial hand-fired-stoker-fired (underfeed and crossfeed)
  - c. Producer-gas manufacture
  - d. Tobacco curing
  - e. Artificial graphite
  - f. Zinc oxide processing—electric-furnace electrodes
2. No. 2 buckwheat (rice)
  - a. Domestic and commercial stokers
  - b. Producer-gas manufacture—brick manufacture
3. No. 3 buckwheat (barley)
  - a. Traveling- and chain-grate stokers
  - b. Admixture with bituminous for smoke abatement
4. No. 4 buckwheat
  - a. Cement kilns—ore sintering—chemical processes
  - b. Traveling- and chain-grate stokers
  - c. Admixture with bituminous for smoke abatement
5. No. 5 buckwheat
  - a. Cement kilns—ore sintering—coke manufacture
  - b. Pulverized burning in combustion units
  - c. Direct ore reduction
  - d. Briquette manufacture—foundry facing
  - e. Brick manufacture
  - f. Chemical processes

<sup>1</sup> KERRICK, J. H., Research Engineer, The Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa., September, 1949.

Table 3-15. Commercial Production of Anthracite by Sizes<sup>1</sup>

Size	Net tons	Per cent	Size	Net tons	Per cent
Broken.....	146,672	0 3	Buckwheat No. 2 (rice)....	4,490,755	7.9
Egg .....	3,201,699	5 6	Buckwheat No. 3 (barley)...	5,793,915	10.1
Stove .....	11,419,511	20 0	Buckwheat No. 4 .....		
Chestnut.....	14,277,938	24 9	Buckwheat No. 5 .....	4,906,299	8 6
Pea .....	5,183,371	9 1	Total commercial production.....	57,183,601	100.0
Buckwheat No. 1 (buckwheat).....	7,763,441	13 5			

<sup>1</sup> Anthracite Committee, 1946. Excludes river coal (1,132,394 tons, mostly rice and smaller) Includes 313,204 tons purchased from "bootleggers."

Table 3-16. Principal Uses of the Fine Sizes of Anthracite<sup>1</sup>  
(In tons)

Size, in.....	$\frac{3}{16} \times \frac{3}{32}$	$\frac{3}{32} \times \frac{3}{64}$	$\frac{3}{64} \times 0$
Use	No. 3 buckwheat (barley)	No. 4 buckwheat	No. 5 buckwheat
Traveling grates	4,560,000	1,447,700	0
Underfeed stokers	504,900 <sup>a</sup>	458,000 <sup>a</sup>	0
Hand firing ..	424,900	5,400	0
Ore sintering .....	98,300	84,000	74,700
Manufacturing carbon electrodes...	15,200	800	800
Manufacturing chemicals .....	1,100	0	0
Manufacturing foundry facings ..	0	0	2,700
Pulverization .....	0	654,600	481,500
Briquetting. ....	4,400	263,800	11,400
Mixed with bituminous .....	1,900	16,900	0
Coke blending .....	0	0	16,300
Special uses (miscellaneous).....	113,300	5,700	2,700
Totals .....	5,724,000	2,936,900	590,100

<sup>1</sup> From figures compiled by Frank C. Wright, Jr., as based upon 1943 usage. Exclusive of colliery boiler fuel, an annual outlet for some 2,000,000 tons of the fine sizes.

<sup>a</sup> Much of this coal is probably mixed with bituminous coal.

### NONFUEL USES OF ANTHRACITE<sup>1</sup>

There are many nonfuel uses of anthracite, and research is today finding additional uses which will have the effect of improving the recovery of the mined product. The following list, though incomplete, gives a rather comprehensive picture of the application of anthracite to uses other than combustion.

1. A filter medium
2. Manufacture of graphite
3. Foundry facings
4. Carbon refractories
5. Electric furnace resistors
6. Heat-transfer tubes
7. Diaphragm plates
8. Carbon structural forms
9. Acid-resisting vats
10. Paint pigment
11. Carbon brushes
12. Carbon electrodes
13. Telephone granular carbon
14. Activated carbon
15. Paper-mill digester plugs
16. Explosives
17. Desludging agent in oil refining
18. Black concrete roads
19. Manufacture of oyster-shell lime
20. Sewage disposal

<sup>1</sup> KERRICK, J. H., Research Engineer, The Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa., September, 1949.

In many of these applications, strict specifications are presented to the industry. With the accordingly improved technology of preparation, there is seldom, if ever, a specification designed to meet a need which cannot be met by some combination of preparation facilities now available in the field.

### PHYSICAL CHARACTERISTICS OF ANTHRACITE

**Weight and Density of Anthracite.** Anthracite varies in bulk density because of the different conditions under which it was formed. Although this difference does not affect the heat value of the coal per pound, it does affect the heat value per cubic foot in direct proportion to the difference in bulk. Therefore, when feeding or burning devices which handle the coal on a bulk rather than a weight basis, as virtually all do, are under consideration, allowances must be made for the density or change in density as between one coal and another. A worm feeder supplying a constant volume of coal per hour, for example, will feed varying amounts of heat units per hour according to the formula

$$\text{Btu input/hr} = (\text{cu ft/hr}) \times (\text{lb/cu ft}) \times (\text{Btu/lb})$$

Other factors affecting the space occupied by a particular size of anthracite include uniformity of sizing, type of coal fracture, and surface moisture.

**Weight and Volume of Anthracite Ash.** The weight and volume of ash are subject to considerable variations, depending upon such factors as (1) the percentage of ash in the coal; (2) the amount of carbon or unburned coal in the ash; and (3) the type of ash, such as whether fine or clinkered, fluffy or compacted. The values in Table 3-17 are thus only approximate ranges for general use.

**Table 3-17. Weight and Volume of Anthracite Ash (Approximations)**

Weight of ash .....	25-45 lb per cu ft
Volume of ash from a ton of coal .....	9-12 cu ft
	7-9 bu

**Table 3-18. Weighted Average Specific Gravities of Anthracite\***  
(By fields and districts)

Field and district	No. of analyses	Sp gr	Ash, per cent	Moisture, per cent
<b>Northern:</b>				
Wanamie and Loree collieries	55	1.58	9.1	5.2
Olyphant and Eddy Creek collieries	41	1.53	9.5	4.5
Field avg .....	96	1.56	9.3	4.9
Eastern middle field avg	22	1.65	8.5	5.1
<b>Western middle:</b>				
Shamokin	15	1.49	11.1	2.3
West Mahanoy	19	1.64	12.5	3.7
Field avg	34	1.57	11.8	3.0
<b>Southern:</b>				
Panther Creek	13	1.65	9.7	3.5
East Schuylkill	6	1.68	11.8	3.5
West Schuylkill	10	1.64	11.4	5.2
Lykens	12	1.52	11.9	3.3
Field avg	41	1.62	11.2	3.9

\* Note that specific gravities shown herein are the "true" specific gravities of the coal in lump, and not the apparent specific gravities of broken coal as marketed and used.

**Table 3-19. Average Specific Gravities of Face Samples of Anthracite from Different Fields<sup>1</sup>**

Field, district, and colliery	No. of analyses	Sp gr	Ash, per cent	Moisture, per cent
<b>Northern field:</b>				
Wanamie No. 18	17	1.60	10.1	5.0
Wanamie No. 19	6	1.55	8.6	5.0
Loree	15	1.59	8.8	5.5
Loree No. 2	5	1.56	9.4	5.4
Loree No. 3	2	1.54	8.1	5.3
Loree No. 4	2	1.60	8.5	5.4
Loree No. 5	8	1.59	8.4	5.7
Olyphant	14	1.51	8.3	4.6
Eddy Creek	27	1.54	10.1	4.4
<b>Eastern middle field:</b>				
Highland No. 5	9	1.64	8.4	5.1
Jeddo No. 7	1	1.66	9.5	5.1
Jeddo No. 4	12	1.65	8.5	5.1
<b>Western middle field:</b>				
Shamokin district, Bear Valley	15	1.49	11.1	2.3
West Mahanoy district, Bast	19	1.64	12.5	3.7
<b>Southern field:</b>				
Panther Creek District, Nesquehoning	11	1.65	9.5	3.4
Coaldale	2	1.65	11.1	3.9
East Schuylkill district, Alliance	6	1.68	11.8	3.5
West Schuylkill district, Pine Knot	10	1.64	11.4	5.2
Lykens Valley, Brookside	7	1.54	13.6	4.3
Short Mountain	5	1.49	9.6	1.9

<sup>1</sup> U.S. Bureau of Mines analyses. Additional information will be found in Analyses of Pennsylvania Anthracite, *U.S. Bur. Mines Tech. Paper*, 659.

**Table 3-20. Bulk Weight of Anthracite**  
(Pounds per cubic foot)

Region Size	Lehigh	Wilkes-Barre	Scranton	Shamokin	Lykens	Avg
Egg	58.9	57.1	54.4	53.1	51.7	55.0
Stove	59.3	57.8	53.8	53.8	51.0	55.1
Chestnut	60.2	58.0	54.2	53.8	50.0	55.2
Pea	57.1	54.4	54.1	52.0	49.8	53.4
Avg	58.9	56.8	54.1	53.2	50.6	54.7

Buckwheat, rice, and barley weigh approximately the same as pea coal.

**Weight and Bulk of Anthracite.** The bulk density of anthracite is due not only to its specific gravity but also to the shape of the pieces and smoothness of surface. In uniformly sized coal, this allows the pieces to distribute well and results in a fuel bed with uniform air passages.

**Table 3-21. Cubic Feet Occupied by 1 Ton of Anthracite**

Region Size	Lehigh	Wilkes-Barre	Scranton	Shamokin	Lykens	Avg
Egg	33.9	35.0	36.8	37.7	38.7	36.4
Stove	33.7	34.6	37.2	37.2	39.2	36.4
Chestnut	33.2	34.5	36.9	37.2	40.0	36.4
Pea	35.0	36.8	37.0	38.5	40.2	37.5
Avg	33.9	35.2	37.0	37.6	39.5	36.6

Buckwheat, rice, and barley occupy approximately the same space as pea.

Table 3-22. Weights per Cubic Foot by Sizes of Typical Commercial Anthracites<sup>1</sup>

Colliery	Size	Lb loose	Lb packed	Lb avg
Dorrance, northern field (in Wilkes-Barre)	Broken. . . .	48.0	52.6	50.3
	Egg . . . .	49.1	53.5	51.3
	Stove. . . .	49.1	54.3	51.7
	Nut . . . .	50.3	54.4	52.3
	Pea . . . .	48.8	53.8	51.3
	Buckwheat . . . .	48.8	53.5	51.2
	Rice . . . .	48.0	53.3	50.6
	Barley . . . .	47.8	53.5	50.6
	No. 4 buckwheat. . . .	46.3	52.0	49.1
Prospect, northern field (at northeast limits of Wilkes-Barre)	Broken. . . .	50.3	54.0	52.1
	Egg . . . .	50.3	54.9	52.6
	Stove . . . .	49.6	55.4	52.5
	Nut . . . .	52.0	56.6	54.3
	Pea . . . .	51.0	56.4	53.7
	Buckwheat . . . .	49.8	54.6	52.2
	Rice . . . .	49.6	55.1	52.4
	Barley . . . .	49.4	55.1	52.3
	No. 4 buckwheat . . . .	48.3	55.6	51.9
	No. 5 buckwheat . . . .	45.8	53.5	49.6
Hazleton shaft, eastern middle field (in Hazleton)	Broken . . . .	52.5	55.7	54.1
	Egg . . . .	53.8	56.8	55.3
	Stove . . . .	55.0	57.2	56.1
	Nut . . . .	55.3	57.7	56.5
	Pea . . . .	54.5	57.0	55.7
	Buckwheat . . . .	53.0	56.1	54.5
	Rice . . . .	52.1	56.6	54.4
	Barley . . . .	51.3	54.5	52.9
	No. 4 buckwheat . . . .	51.0	54.5	52.8
Spring Mountain, eastern middle field (southwest of Hazleton)	Egg . . . .	54.4	56.4	55.4
	Stove . . . .	54.2	56.6	55.4
	Nut . . . .	54.4	56.3	55.3
	Pea . . . .	52.4	55.7	54.1
	Buckwheat . . . .	52.4	55.3	53.8
	Rice . . . .	51.5	55.2	53.4
	Barley . . . .	52.2	55.7	54.0
	No. 4 buckwheat . . . .	48.6	53.3	51.0

<sup>1</sup> Lehigh Valley Coal Co.

Table 3-23. Analyses and Physical Properties of Barley Anthracite

Properties	Approx ranges	Avg of 41 breakers <sup>a</sup>
Proximate analyses:		
Volatile matter, per cent	3.0-8.0	4.4
Fixed carbon, per cent	77-86	82.1
Ash, per cent	9.5-17.5	13.6
Sulphur, per cent. . . . .	0.5-1.2	0.7
Per cent fixed carbon, dry mineral-matter-free basis	92-98	
Heat value, Btu, dry basis	12,000-13,600	12,890
Moisture (as received), per cent.	5-7	7.2 <sup>b</sup>
Softening temp of ash, deg F	2400-3000	2800
Approximate ignition temp, deg F	525-775	
Weight and volume:		
Sp gr . . . . .	1.45-1.75	
Lb per cu ft . . . . .	50-60	
Cu ft occupied by 1 ton	33-40	
Tendency to spontaneous combustion		None
Grate recommended:		
Proper type . . . . .	Stationary or dumping	
Max size of air opening . . . . .	3/4-3/2	
Free air space, per cent. . . . .	4-10	
Combustion rate:		
Hand-fired . . . . .	15-20	
Hand or semistokers . . . . .	18-23	
Traveling-grate stokers. . . . .	20-40	
Availability:		
Tons mined in 1942 . . . . .	5,800,000	
Per cent of total breaker production	10.0	
Approximate F.O.B. mines cost (1942)	\$2.50	

<sup>a</sup> Based upon U.S. Bur. Mines Repts. Invest. 3283, 1935, analyzing 268 samples from 41 breakers mining 50 per cent of all anthracite.<sup>b</sup> Measured at breaker.



## COMPARISON BETWEEN FRESH-MINED AND WEATHERED COAL

According to Sisler, Fraser, and Ashmead,<sup>1</sup> the calorific value of the coal in silt banks that have stood for some time is a little lower than that of fresh, mined coal of the same ash content. This deterioration varies with the age of the bank and was over 4 per cent in the most extreme case of weathering. They found that the coal in banks which are in use for storing silt and which have accumulated for 5 to 10 years has 100 to 200 Btu per lb lower calorific value than fresh-mined coal of the same ash content from the same colliery. In banks that have been exposed for 40 years, this difference is as much as 500 Btu per lb.

Actual comparisons between reclaimed and fresh-mined coal from the same mine at Girardville, Schuylkill County, also show an average difference of 270 Btu for seven sizes. However, in this case there was also a 0.93 per cent difference in the ash content which could account for the lower Btu of the weathered sample instead of the exposure. As both the weathered and the deep-mined coals were cleaned on the same equipment,<sup>2</sup> it is not known whether the difference in ash can be attributed to weathering or not (see Table 3-24).

Table 3-24. Comparison between Fresh-mined and Weathered Anthracite  
(Location: Girardville, Schuylkill County)

	Stove	Chest-nut	Pea	Buck-wheat	Rice	Barley	No. 4 buck-wheat	Avg
Moisture, as received:								
Fresh . . . . .	4 0	4 0	4 5	4 5	5 0	6 0	6 0	4 86
Weathered . . . . .	4.5	4 5	4 7	4.8	5 0	6.0	6 0	5 11
Volatile dry:								
Fresh . . . . .	4 4	4 4	4.5	4.6	4 8	4.8	4 8	4 61
Weathered . . . . .	4 6	4 6	4 8	5.0	5 0	5.0	5 0	4 86
Fixed carbon dry:								
Fresh . . . . .	86 6	86 6	85 5	84.9	84 2	84.2	84 2	84 59
Weathered . . . . .	84 9	84 9	84.7	84.0	83 5	83.0	83.0	84.00
Ash, dry:								
Fresh . . . . .	9 0	9 0	10.0	10.5	11 0	11.0	11 0	10.21
Weathered . . . . .	10 5	10.5	10.5	11.0	11.5	12 0	12.0	11 41
Sulphur, dry:								
Fresh . . . . .	0 6	0 6	0.6	0.6	0.6	0.6	0.6	0.60
Weathered . . . . .	0 6	0.6	0.6	0.6	0 6	0.6	0.6	0.60
Btu/lb dry:								
Fresh . . . . .	13,550	13,550	13,410	13,335	13,250	13,250	13,250	13,413
Weathered . . . . .	13,250	13,250	13,250	13,175	13,075	13,000	13,000	13,143
Ash fusion:								
Fresh . . . . .	2,950	2,950	2,950	2,950	2,950	2,950	2,950	2,950
Weathered . . . . .	2,920	2,920	2,920	2,920	2,920	2,920	2,920	2,920

Other investigators report somewhat more difficult ignition with weathered coal, which has been variously attributed to (1) a natural distillation of the lighter volatiles, (2) surface coatings of thin noncombustible films, and (3) surface oxidation.

Weathered samples frequently show abnormally high percentages of volatile matter. This is attributable to water of hydration in the ash-forming minerals of the sample and does not represent an increase in the percentage of combustible volatile matter.

One point is reasonably certain, and that is that any appreciable deterioration of anthracite on any point of analysis will be only as the result of *years* of storage and not

<sup>1</sup> SISLER, J. D., T. FRASER, and D. C. ASHMEAD, "Anthracite Culm and Silt," *Pennsylvania Geological Survey Bull.* M-12, 4th Ser., p. 19, 1928.

<sup>2</sup> Chance cones for stove and nut, hydrotators for pea and smaller.

of the seasonal or year-to-year storage encountered in industry or at the consumer level.

### Discoloration of Bank Coal

A study of the red and yellow discolorations commonly found on bank and other weathered coal indicates that it is the precipitation of the different chemical agents which have been leached from the slates, shales, stones, and minerals by the water which has come in contact with the coal during storage.

A qualitative analysis of typical stains (Table 3-25) shows the presence of traces of chlorides, carbonates, and silicates; sulphur as both sulphates and sulphides; iron and aluminum as oxides; and traces of calcium and magnesium as oxides.

**Table 3-25. Typical Composition of Stains on Weathered Coal**  
(In grams per gram of anthracite)

	Red stain	Yellow stain		Red stain	Yellow stain
Silicates .....	Trace	Trace	Iron oxide.....	0 0019	0.0048
Chlorides .....	Trace	Trace	Alumina.....	0 0003	Trace
Carbonates .....	Trace	Trace	Lime.....	0 0003	Trace
Sulphates .....	0 0016	0 0010	Magnesia .....	Trace	Trace
Sulphides .....	0.0002	0.0001			

**Table 3-26. Typical Analyses of Anthracite Reclaimed from "Banks"<sup>1</sup>**

County, town, and operation	Coal size	Proximate analysis (dry), per cent				Btu, dry basis	Ash-softening temp, deg F
		Volatile	Fixed carbon	Ash	Sulphur		
Luzerne County:							
Avoca (Langcliffe) ....	Nut	6 9	76 4	16 7	0 7	12,220	
	Pea	7 3	80 5	12 2	0 7	12,900	
	Buckwheat	7 5	79 0	13 5	0 6	12,650	
Milnesville (Coldspring) .	Stove	4 3	84 8	10 9	0 7	13,100	
	Nut	4 6	84 6	10 8	0 7	13,100	
	Pea	4 5	81 8	13 7	0 7	12,610	
	Buckwheat	5 2	77 5	17 3	0 6	12,050	
	Rice	5 1	83 4	11 5	0 7	12,890	
	Barley	5 7	79 9	14 4	0 6	12,430	
Schuylkill County:							
Branch Dale (Otto).....	Nut	6 1	80 3	13 6	0 5	12,690	2,860
	Pea	6 1	80 2	13 7	0 5	12,610	2,860
	Buckwheat	7 0	78 7	14 3	0 6	12,610	2,910+
	Rice	6 8	80 7	12 5	0 5	12,630	2,910+
	Barley	7 6	80 2	12 2	0 6	12,840	
Gilberton (Gilberton).....	Stove	5 0	79 6	15 4	0 6	12,450	2,910+
	Nut	4 4	80 7	14 9	0 6	12,470	2,910+
	Pea	4 9	79 5	15 6	0 6	12,400	
	Barley	5 7	80 5	13 8	0 5	12,530	
Girardville.....	Buckwheat	5 6	79 7	14 7	0 5	12,450	
	Barley	5 7	77 6	16 7	0 5	12,150	

<sup>1</sup> Analyses of Pennsylvania Anthracitic Coals, *U.S. Bur. Mines Tech. Paper 659*.

**River coal**, which in 1946 accounted for the remaining 2 per cent of production, is coal which has been washed into streams and rivers draining the region, principally the Susquehanna and Schuylkill, and to a lesser extent the Lehigh, during the course of mining, preparation, and storage. While accurate estimates are impossible, Sisler, Fraser, and Ashmead estimated that as of 1928 there were at least 900,000,000 tons of

material on the river bottoms which contained sufficient percentages of coal to make working profitable. In 1946, a total of 1,132,394 net tons were mined. The size distribution of the 886,693 tons shipped to market as shown in Table 3-27 is as reported by the U.S. Bureau of Mines (see Table 3-28 for typical analyses).

**Table 3-27. "River Anthracite"  
Shipped in 1946**

	Net Tons
Pes.....	605
Buckwheat No. 1 .....	7,657
Buckwheat No. 2 (rice) .....	40,319
Buckwheat No. 3 (barley).....	164,304
Buckwheat No. 4 .....	276,515
Other, including silt.....	397,239
Total.....	886,639

"Bootlegging," tonnages of which are not generally included in published industry totals, accounts for the only remaining source of anthracite. About 1,450,000 net tons were mined in 1946. As of March, 1947, 863 "bootleg" holes were being worked by 2,817 men. Originally started as a company-tolerated means for furnishing heat for the diggers'

individual homes during the darkest days of the depression, the practice soon far outreached this scale to reach a peak of over 6 million tons (1941). Basically the coal is the same as that from strippings, but the crude preparation plants almost ensure high ash, poor sizing, and questionable weights.

**Table 3-28. Typical Analyses of Anthracite "River" Coal<sup>1</sup>**

County, town, and operation	Proximate analysis (dry), per cent				Btu, dry basis	Ash-softening temp, deg F
	Volatile	Fixed carbon	Ash	Sulphur		
<b>Dauphin County:</b>						
<b>Harrisburg:</b>						
Cedar Street Landing .....	7 0	75 8	17 2	0 5	12,120	2,760
Clarks Ferry Landing .....	7 3	76 6	16 1	0 5	12,280	2,790
Coxtown Landing .....	7 0	76 6	16 4	0 6	12,250	2,860
Paxton Street Landing .....	7 1	73 9	19 0	0 6	11,800	2,760
<b>Lancaster County:</b>						
Holtwood Dam .....	8 4	76 2	15 4	0 6	12,440	2,730
Holtwood Dam (culm) .....	7 5	76 1	16 4	0 7	12,310	2,800
Holtwood Dam (Pequea).....	7 8	72 2	20 0	0 5	11,750	2,440
<b>Northumberland County:</b>						
Dornsife (Barton) barley <sup>a</sup> ..	7 1	73 8	19 1	0 6	11,840	2,910+
Paxinos (Shamrock) .....	7 8	77 8	14 4	0 7	12,870	2,890
Snydertown (Dalton) barley ..	8 0	75 1	16 9	0 8	12,350	2,880
Snydertown (Kulp) Nos. 4 and 5 buckwheat ..	8 2	80 8	11 0	0 7	13,260	2,800
Snydertown (Saville) barley ..	8 3	75 4	16 3	0 7	12,430	2,750
Snydertown (Saville) Nos. 4 and 5 buckwheat ..	8 6	78 3	13 1	0 7	12,920	2,690
<b>Schuylkill County:</b>						
Gordon (Barry) No. 4 buckwheat. .	6 6	80 0	13 4	0 6	12,580	2,880
Gordon (Gordon) rice .....	5 7	74 0	20 3	0 5	11,670	2,910+
Reynolds (Reynolds) buckwheat ..	5 2	81 4	13 4	0 5	12,570	2,920+
Reynolds (Reynolds) rice .....	4 8	84 0	11 2	0 5	13,040	2,910+
Reynolds (Reynolds) No. 5 buckwheat	4 9	81 2	13 9	0 4	12,580	2,850

<sup>1</sup> Analyses of Pennsylvania Anthracitic Coals, U.S. Bur. Mines Tech. Paper 659.

<sup>a</sup> Semianthracite.

### MIXTURES OF BITUMINOUS COAL AND ANTHRACITE<sup>1</sup>

Field tests of various mixtures of bituminous slack coal and anthracite, barley size and smaller, on industrial stokers show that the use of such mixtures is very practical

<sup>1</sup> BARKLEY, J. F., L. R. BURDICK, and R. WIGGERS, Tests of Bituminous-anthracite Mixtures on Industrial Stokers, U.S. Bur. Mines Repts. Invest. 3916, May, 1946. FRNN, E. E., "Admixture of Anthracite to Bituminous Coal," Anthracite Institute mimeographed undated release.

and that improved conditions may result where one or more of the following factors prevails:

1. The mixture will produce a resultant price advantage in the locality.
2. Smoke is an objectionable factor.
3. It is difficult to obtain low-volatile bituminous coal, or high-volatile mixed with anthracite to approximate low-volatile results in material savings of fuel cost.
4. Bituminous coal, either hand- or stoker-fired, is used in domestic furnaces.
5. Coke is produced. (The U.S. Bureau of Mines states that anthracite No. 4 or No. 5 buckwheat can be mixed successfully with bituminous coal in the production of coke in proportions of 5 to 10 per cent.)

**Advantages and Disadvantages.** Advantages of bituminous-anthracite mixtures include ability to approximate low-volatile performance with high-volatile in the mix, improved uniformity of the fuel bed of single-retort stokers with resultant less manual attention, decreased smoke, a general lessening of clinker, improved banking conditions, and weakening of the coke and coke-tree structure.

Disadvantages include increased fly ash (with smaller anthracite sizes only), increased combustible in the fly ash and refuse, and a tendency to reduce the peak-load carrying capacity, especially with the higher percentages of anthracite.

In general, the efficiencies obtained on single-retort stokers with the lower percentages of anthracite in the mixtures are about the same as with bituminous coal only; with the higher percentages of anthracite the over-all efficiencies were found to be somewhat lower (Fig. 3-4).<sup>1</sup>

**Percentage to Mix.** The best percentage of anthracite to use at a given installation depends on many factors, such as the size consist, the volatile and ash content, the ash fusion of the fuels to be used, the load conditions, the smoke production, and the type of equipment available. It should be determined by trial for each installation.

Finn gives the following very general rules for determining the mixture:

1. It is generally safe to start with 25 per cent anthracite. After the fireman has become thoroughly familiar with this mix, it may be increased if conditions and peak-load performance warrant.

2. An excess over 25 per cent is usually possible where the boiler load is uniform or where an exceptionally high-volatile coal is in use.

3. Bituminous coal-anthracite mixtures are usually less advantageous with low-volatile bituminous. A trial mixture should not be over 10 to 15 per cent anthracite.

In very general terms, the poorer and less satisfactory the bituminous coal, the more advantageous the mix and the greater the percentage that can be mixed advantageously.

**Size of Anthracite.** General rules for the selection of a size of anthracite to mix are: (1) buckwheat or rice may be used with run-of-mine bituminous (although this mixture is less satisfactory than those of the more homogeneous sizes because of the difficulty of retaining the mixture and of securing uniform burnouts); (2) rice or barley can be used with nut and slack bituminous; and (3) barley, No. 4 or No. 5 buckwheat can be used with bituminous-coal slack.

**Method of Mixing.** The method of mixing will necessarily be dictated by the type and size of the plant and the equipment available. The Bureau of Mines says, "It is a mistake to conceive that the needed mixture must be a 100 per cent thoroughly uniform fuel before it enters the stoker; it should not, however, have large, segregated batches of anthracite. Considerable mixing occurs in the stoker itself. The higher the percentage of bituminous coal fines, the more readily the anthracite particle can

<sup>1</sup> Finn points out that, where the combustion space is too small to burn all the volatile gases properly, a mixture of anthracite may definitely increase the boiler output by reducing the escape of unburned fuel.

be coated. The higher the percentage of anthracite, the more careful must be the external mixing."

In mixing by loading alternate layers of anthracite and bituminous coal on a truck, it is important to load the anthracite on the bottom. Finn also calls attention to the proved effectiveness of using the layer method of barge loading.

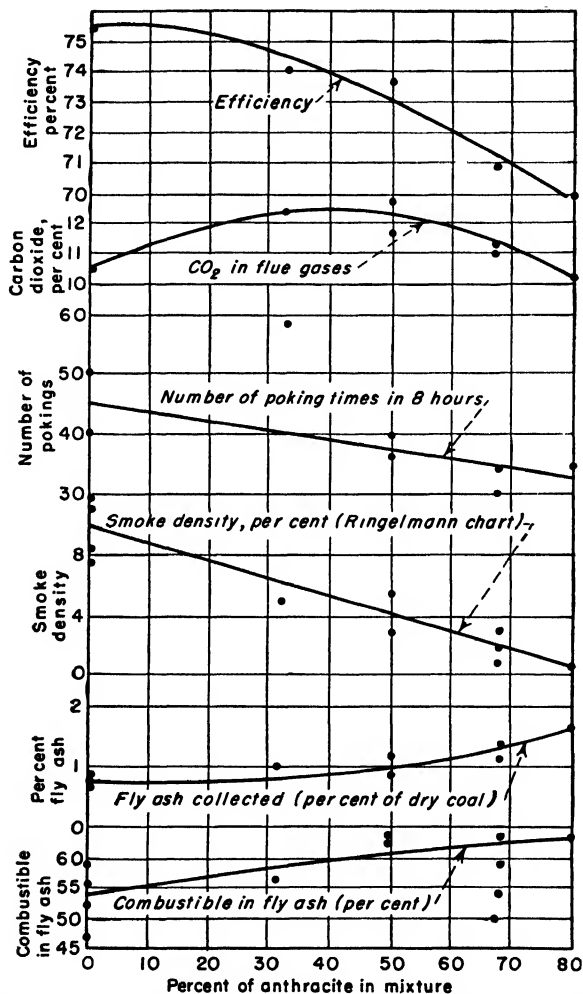


FIG. 3-4. Effect of various percentages of anthracite in mixtures of bituminous coal and anthracite. (U.S. Bureau of Mines, Rept. Invest. 3916.)

**Use of Admixtures for Pulverized-coal Firing.** Tests conducted in 1936 by Berger<sup>1</sup> on the Phillipsburg, N.J., plant of the Baker Chemical Co., are still the best available comparison of pulverized anthracite, bituminous coal, and admixtures.

<sup>1</sup> BERGER, J. G., Consulting Engineer, Newark, N.J., Engineering Report Covering Acceptance Tests, Observation Run, Recommendations, and Final Conclusions Relative to New Boiler Plant of the J. T. Baker Chemical Company, Phillipsburg, N.J., Feb. 1, 1936. Private report, quoted by permission.

The plant consisted of one 400-hp Keeler, two-longitudinal-drum water-tube boiler; Kennedy-Van Saun air-swept tube mill, 5 by 7 ft; DeWolf suspended air-cooled walls for the sides and rear, with firebrick floor. No superheater or economizer. Coal was fed by a 30-in.-diameter disk feeder with  $\frac{1}{4}$ -hp motor. Burners consisted of two Kennedy Vortex, downfiring, size 2 by 18 in., under which were water-cooled deflector bars.

The condensed results of three 8-hr (nominal) tests on anthracite, a 50:50 mixture of anthracite and bituminous coal, and bituminous coal are as shown in Table 3-29.

**Table 3-29. Comparison of Bituminous Coal, Anthracite, and Admixtures for Pulverized-coal Firing<sup>1</sup>**

	Anthracite No. 4 buck- wheat	Admixtures 50:50 mix	Bituminous coal
<b>Coal analyses (dry basis):</b>			
Volatile matter, per cent. . . . .	5 94	11 81	32 48
Fixed carbon, per cent. . . . .	82 97	78 75	58 72
Ash, per cent. . . . .	11 09	9 44	8.80
Sulphur, per cent. . . . .	0 54	1 19	1.44
Heat value per lb, Btu . . . . .	13,510	14,080	14,260
<b>Heat balance:</b>			
Heat absorbed (efficiency), per cent . . . . .	81.68	85 27	80.73
Loss to evaporation moisture, per cent . . . . .	1.03	0.65	0.86
Loss to hydrogen, per cent . . . . .	2.06	2 84	3.73
Loss to dry flue gas . . . . .	10.13	9.90	7.45
Loss to carbon monoxide, per cent . . . . .	0 0	0.0	0.0
Loss to combustible in ash, per cent . . . . .	0 0	0.0	0 0
Loss unaccounted for, per cent. . . . .	5.1	1.34	7.23
<b>Totals and averages:</b>			
Temp of flue gas, deg F. . . . .	449	456	469
Draft at boiler outlet, in . . . . .	0 2	0.239	0 25
Draft in furnace, in. . . . .	0 05	0 052	0.06
Temp air for combustion, deg F. . . . .	184	208	223
Temp secondary air, deg F. . . . .	238	220	232
Dry coal fired per hr, lb. . . . .	1,450	1,380	1,548
Equivalent evaporation per sq ft heat surface, lb	4 12	4.26	4.59
Bhp developed . . . . .	477	493	533
Per cent rated capacity . . . . .	119	123	133
Evaporation per lb dry coal, lb . . . . .	11 10	11.90	11.58
Equivalent evaporation per lb coal as fired, lb . . . . .	10.21	11.52	10.78
Equivalent evaporation from and at 212°F, lb . . . . .	11.37	12.37	11.85
<b>Analysis of stack gases:</b>			
Carbon dioxide (Orsat), per cent. . . . .	13.72	13 35	13.16
Oxygen, per cent . . . . .	4 4	4 8	4.23
Carbon monoxide, per cent . . . . .	0	0	0
Nitrogen (by difference), per cent . . . . .	81.88	81.85	82.61
Per cent excess air . . . . .	26	28	24

<sup>1</sup> Data condensed from acceptance test and report of J. G. Berger, Consulting Engineer, Newark, N.J., on Phillipsburg, N.J., plant of Baker Chemical Co. Reproduced by permission.

It will be noted that the efficiency was highest with the admixture. The use of both anthracite and admixtures depressed the boiler ratings somewhat, the figures being 133 per cent for bituminous, 123 per cent for the admixture, and 119 per cent for anthracite.

As to operating results, Berger comments that there is danger of loss of ignition with straight anthracite under certain conditions. When only a partial loss occurs, it lands as a sticky mass on the floor or rear wall and slags; whereas, if the bituminous admixed ignites it sooner, it will burn out to ash before striking a cooling surface and thus not slag. The admixture was reported to be very much better from the slagging angle than anthracite, and the flame propagation was very satisfactory.

**Admixtures for Cement Manufacture.** According to Harrington,<sup>1</sup> the use of straight anthracite, while theoretically possible, has not as yet proved entirely satisfactory in cementmaking. High autoclaves and high free-lime clinker will result if the kiln is not very closely watched. However, Harrington strongly recommends the use of admixtures of anthracite and bituminous coal.

When starting the use of admixtures for the first time, he suggests 20 per cent anthracite in the mix, with gradual increase to a limiting condition under close supervision of an experienced operator. The following conditions are important: (1) per cent moisture in the "as-fired" coal mixture should be 3 per cent or under and will definitely give inferior results above 4 per cent; (2) a uniform mixture of the two coals must be maintained, as an uneven mixture will give a sputtering and surging flame and cool the burning zone of the kiln; (3) a coal-air temperature of 250 to 280°F should be maintained, burned as close to the nozzle (6 to 18 in.) as practicable—this should give rapid combustion and a maximum burnout of the anthracite; and (4) pulverization recommended is at least 80 per cent through a 200-mesh screen, and 90 per cent through 100-mesh.

The use of anthracite usually results in substantial savings in those mills located within an area of favorable freight rates. Such savings can be readily calculated on a basis of prevailing prices.

## ANTHRACITIC COALS<sup>2</sup>

(Other Than Pennsylvania Anthracite)

Anthracitic coals are known to occur in eight states, Arkansas, Colorado, Pennsylvania, Massachusetts, New Mexico, Rhode Island, Virginia, and Washington, with the possibility of isolated noncommercial deposits as a part of seams of other ranks in other states.

Anthracitic coals have been divided into three groups: (1) meta-anthracite, a high-carbon coal that is usually very slow to kindle and difficult to burn; (2) anthracite, a high-carbon low-volatile coal of widely accepted value as both a domestic and industrial fuel; and (3) semianthracite, a coal lying between anthracite and bituminous coal in carbon and volatile content, and also, generally speaking, in burning characteristics.

## META-ANTHRACITE AND GRAPHITIC ANTHRACITE

There are few if any extensive deposits of meta-anthracite in the United States. Some of the anthracites of Rhode Island contain almost negligible quantities of volatile and would thus fall into the meta-anthracite grouping on a basis of analysis alone. However, their other characteristics indicate that they should be considered as graphite.

This material is being mined for use as foundry facings and furnace linings. A typical analysis of Fenners Lodge graphite, from Rhode Island, is graphitic carbon, 55.9 per cent; silica (ash), 40.6 per cent; sulphur, 1.6 per cent; moisture, 9.1 per cent; volatile, 0 per cent.

Other Rhode Island coals possess percentages of volatile that would throw them

**Table 3-30. Estimated Total Reserves of Anthracitic Coals**

(Net tons)	
Pennsylvania.....	15,000,000,000*
Virginia .....	489,000,000
Arkansas. ....	223,000,000
Colorado .....	91,000,000
New Mexico.....	(Not estimated)
Washington.....	23,000,000
Total .....	15,826,000,000

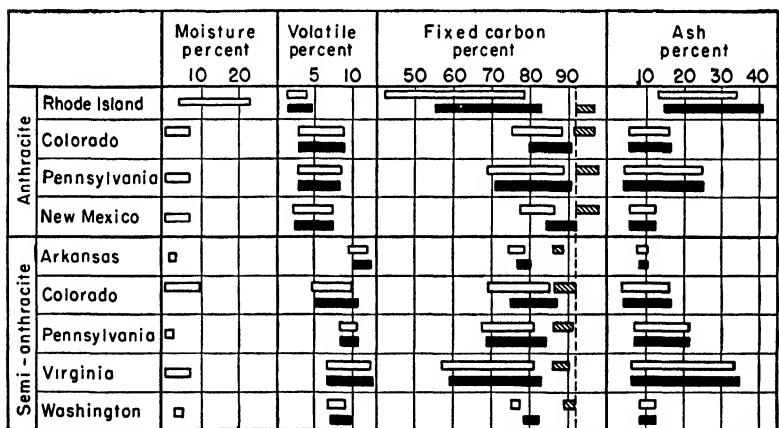
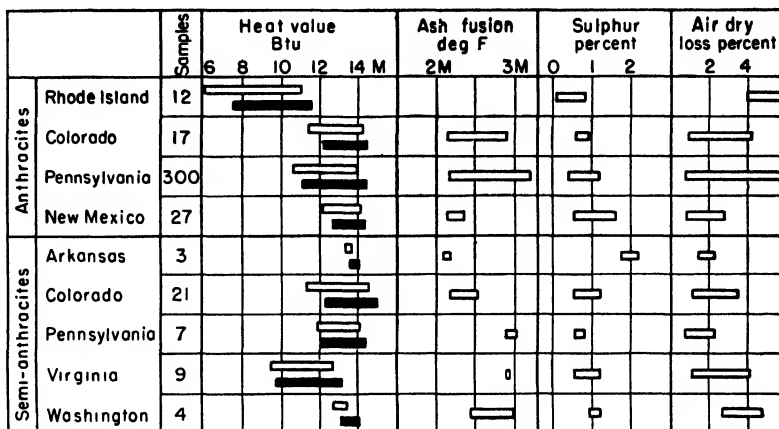
\* Includes Pennsylvania anthracite.

<sup>1</sup> HARRINGTON, PATRICK D., Combustion Engineer, Alpha Portland Cement Co., Easton, Pa., as reported in the July, 1949, issue of *Pit and Quarry*.

<sup>2</sup> JOHNSON, ALLEN J., Anthracites and Semianthracites in the United States, *Trans. AIME Coal Div.*, vol. 157, 1944.

into the normal anthracite rather than the meta-anthracite class. However, this "volatile" is nearly all noncombustible, being composed almost entirely of carbon dioxide and inert gases; therefore, its definition as volatile is open to discussion.

The Narragansett field of Rhode Island and Massachusetts is a basin of 1,000 sq miles, roughly including the part of Rhode Island that is east of Providence as well as the southeastern part of Massachusetts south of Brockton and east of the Massachusetts-Rhode Island state line.



— Coal as received    ■ Coal on a dry basis    ▨ Moisture mineral matter free

Fig. 3-5. Range of analytical values for anthracite coals. (AIME, 1944.)

The coal is extremely variable in character and quality, ranging from anthracite to graphite. Virtually all this coal possesses common undesirable characteristics.

These coal beds are neither uniform in thickness nor continuous. Compression has resulted in squeezing the plastic coal into more or less lenslike masses. As a result, the coal is so sheared and fractured that it possesses little coherence and is extremely friable, thus yielding a very large percentage of the smaller sizes.

The fracturing of the coal has permitted the percolation of mineral-bearing solutions which have deposited a material similar to asbestos or asbestos quartz throughout the



**Table 3-31. Commercial Sizing of Anthracitic Coals in the United States\***  
(All dimensions in inches)

Size	Anthracites		Semianthracites (Arkansas)	
	Pennsylvania	New Mexico	Bernice	Sparda
Block				14 × 7
Grate and broken	4 $\frac{3}{8}$ × 3 $\frac{1}{4}$ -3 (broken)	4 × 2 $\frac{1}{2}$	7 $\frac{1}{2}$ × 4 $\frac{1}{4}$	
Furnace ..			7 $\frac{1}{2}$ × 2 $\frac{1}{4}$	5 × 2 $\frac{1}{4}$
Egg . . .	3 $\frac{1}{4}$ -3 × 2 $\frac{1}{16}$	2 $\frac{1}{2}$ × 2 $\frac{1}{4}$	4 $\frac{1}{4}$ × 2 $\frac{1}{2}$	5 × 2 $\frac{1}{4}$
Stove. . .	2 $\frac{1}{16}$ × 1 $\frac{3}{8}$		2 $\frac{1}{4}$ × $\frac{1}{2}$	2 $\frac{1}{4}$ × 1 $\frac{1}{2}$
Range . .			2 $\frac{1}{4}$ × $\frac{5}{8}$	
Base burner		1 $\frac{1}{2}$ × $\frac{1}{8}$		
Nut . . .			1 $\frac{1}{4}$ × $\frac{3}{8}$	1 $\frac{1}{2}$ × $\frac{3}{8}$
Chestnut	1 $\frac{3}{8}$ × 1 $\frac{3}{16}$	1 $\frac{1}{2}$ × $\frac{1}{2}$	1 × $\frac{5}{8}$	1 × $\frac{1}{8}$
Pea . . .	1 $\frac{3}{16}$ × $\frac{5}{16}$	$\frac{3}{8}$ × $\frac{1}{2}$	$\frac{3}{8}$ × $\frac{5}{8}$	$\frac{3}{8}$ × $\frac{5}{8}$
Buckwheat	$\frac{5}{16}$ × $\frac{5}{16}$	$\frac{1}{2}$ × $\frac{5}{16}$		
Buckwheat No. 2	$\frac{5}{16}$ × $\frac{3}{16}$			
Buckwheat No. 3	$\frac{3}{16}$ × $\frac{5}{32}$			
Buckwheat No. 4	$\frac{5}{32}$ × $\frac{5}{16}$			
Buckwheat No. 5	$\frac{5}{16}$ × 0			
Duff.....		$\frac{5}{16}$ × 0		
Slack .....				$\frac{5}{8}$ × 0

\* See Tables 3-6 and 3-7 for complete sizing tables for Pennsylvania anthracite.

coal, thus materially increasing the percentage of noncombustible and rendering ignition extremely difficult.

Coal from the Narragansett field is hygroscopic, especially in the smaller sizes. As much as 15 per cent moisture will be absorbed by dry coal in a relatively short exposure to moist air. As a result, the Btu value is largely dependent upon the conditions of mining and storage. Air-dried coal will reach 10,000 or even 11,000 Btu, but the same coal may drop to 6,000 to 8,000 Btu upon exposure to moisture.

**Table 3-32. Average Analyses of Various Anthracitic Coals by States<sup>1</sup>**

Location		Group- ing	Number of sam- ples	Proximate analyses, per cent					Heat value, Btu, dry	Ash- soft- ening temp, deg F
State	Type coal			Mois- ture	Vola- tile	Fixed car- bon	Ash	Sul- phur		
Rhode Island.	"Graphitic" an- thracite	96 8	12	11 8	2 8	62.4	23 0	0.3	9,958	
Pennsylvania	Anthracite	95 1	268	5 5	4.2	79.9	10 4	0.7	13,330	2890
Colorado . . .	Anthracite	94 2	17	4 7	4 9	80 8	9 6	0 7	13,570	2450
New Mexico...	Anthracite	93 3	115	3.9	5 8	81 9	8 3	1.0	13,610	2220
Arkansas.....	Semianthracite	87 8	3	2 4	10 7	77.3	9 6	1.9	13,865	2180
Colorado.....	Semianthracite	90 2	77	4.0	8 6	79 3	8.1	0.7	13,840	2340
Pennsylvania.	Semianthracite	88 8	6	1.9	9 5	75 6	13 1	0 6	13,340	2950+
Virginia.....	Semianthracite	86 8	10	4 3	10.2	67.9	17 8	0.7	12,500	2930
Washington...	Semianthracite	90.7	4	5 2	7.8	77 0	11.6	1.0	13,600	2630

<sup>1</sup> JOHNSON, ALLEN J., "Anthracites and Semi-anthracites in the United States," AIME.

Additional disadvantages include "explosive" burning because of entrained moisture, clinkering, and difficulty in washing with conventional equipment, owing to high specific gravity (average of eight samples equals 2.00 specific gravity).

One ton of this coal occupies 25 to 30 cu ft as compared with 35 to 40 cu ft for anthracite.

Special handling, specific equipment, and undercover storage are practically requisites.

A report to the Massachusetts Legislature summarizes the advantages and disadvantages of Narragansett field anthracite as follows:

*Disadvantages.* (1) Irregular form and thickness of the coal beds, (2) intimate fracturing and friability of the coal, (3) large percentage of fine material in mining (main mine output would contain a large percentage of the smaller sizes), (4) high content of noncombustible material or ash, (5) high moisture content, (6) low heating value, (7) difficulty of combustion, and (8) continual attendance necessary in burning it.

*Advantages.* Location in an industrial region that is some distance from the nearest available fuel; hence low cost of delivery.

### SEMIANTHRACITE

As coals cover a continuous range of analyses, any dividing line between anthracite and semianthracite must necessarily be arbitrary. This has been set at 92 per cent moisture- and mineral-matter-free fixed carbon, not only because it seemed to be a logical division from a point of customary usage and nomenclature, but also, and more important, because coals below 92 per cent give a tar deposit upon combustion and coals above 92 per cent do not. Furthermore, semianthracites, by reason of higher volatile, burn faster and usually, although not always, clinker more readily. Therefore, the distinction between anthracite and semianthracite is an important one, especially in areas where both are obtainable.

The principal practical differences between the physical properties of Pennsylvania anthracite and semianthracite are a higher volatile content with a tar deposit after combustion, somewhat more distinct laminations due to luster contrasts, more of a tendency toward a rectangular rather than conchoidal fracture, lower specific gravity (below 1.47), somewhat softer body (2.50 to 2.75 as against 2.75 to 3.00), and more friable (50 per cent as against 35 per cent).

These differences are difficult to detect by any means other than through an analysis and determination of the moisture- and mineral-matter-free percentages of fixed carbon.

Semianthracite frequently is found as a part of veins or measures having a general bituminous or anthracite grouping. However, the principal deposits of semianthracite in the United States are in Arkansas, Pennsylvania (Sullivan County), Virginia, and Washington.

**Arkansas.** Relatively extensive deposits of semianthracite are located in Pope and Johnson Counties, in western Arkansas. Production represents about 15 per cent of the state's output of coal.

Although the Arkansas Geological Survey divides this field into four districts, the entire area usually is referred to as the Sparda field, subdivided into the Bernice or Russellville field in southeast Pope County and the Sparda bed in the northwest (Johnson County).

The coal beds are well exposed in this region and have suffered considerable folding, faulting, and erosion.

The principal seam mined, the Hartshorne, has coals of three different ranks in different localities—semianthracite, low-volatile, and medium-volatile bituminous.

Because this coal is the hardest in structure and lowest in volatile found in this region, it is frequently called "Arkansas anthracite," although the analysis clearly indicates that it is semianthracite in rank.

As is frequently characteristic of semianthracite, the ash-fusion temperature is low, the average being about 2180°F. The sulphur content is high as compared with other anthracitic coals (1.7 to 2.2 per cent). The excessive folding of the region has produced a coal of high friability and large percentages of small sizes.

Since the inauguration of an effective smoke-prevention campaign in St. Louis, this fuel has been in considerable demand.

**Pennsylvania.** In Pennsylvania semianthracite is found in Sullivan County and in the western part of Wyoming County. Mines are at Bernice (Connell), Laporte (Rock Run), and Forksville (Monahan), Sullivan County.

Some coal at the extreme western tips of the Pennsylvania anthracite region's western middle fields (Northumberland County) and southern field (Dauphin County) analyze as semianthracites.

**Virginia.** Semianthracite is mined extensively in the Brushy Mountain field of Pulaski, Wythe, and Montgomery Counties in Virginia. Although small (3 per cent) as compared with the Pennsylvania anthracite reserves, the estimated half a billion tons of semianthracite in Virginia nevertheless forms the second largest reserve of anthracite coals in the United States. Furthermore, because of proximity to Pennsylvania anthracite markets, this coal frequently is sold in competition under the common trade name "Virginia anthracite."

The highest moisture- and mineral-matter-free fixed carbon of any sample reported by the Bureau of Mines was 90 per cent—two full per cent below the 92 per cent border line between anthracite and semianthracite. The volatile analyzes as high as 12.6 per cent, with an average of 10.2 per cent, and the ash as high as 33.8 per cent (delivered sample) with a 17.8 per cent average.

In one series of comparative tests, Virginia semianthracite was found to have a use value of approximately 88 per cent of that of Pennsylvania anthracite. As is characteristic of semianthracite, it burned much more rapidly, and some soot was emitted.

**Washington.** Semianthracite in the state of Washington lies in the extreme northwestern county (Whatcom) on a ridge south of Glacier Creek and northwest of Mount Baker.

The thickness of veins extends to 14 ft or more, but much of it is in the form of finely disintegrated, crushed, and weathered fragments, which appear to be soft. Impure laminated coal also usually forms a substantial part of the veins.

No production on a commercial scale has yet taken place.

**Colorado.** In Colorado, both anthracite and semianthracite are found in the Crested Butte field of Gunnison County. There is also a small isolated deposit of semianthracite in the Green River bituminous field of Routt County, northwest of the town of Steamboat Springs.

Semianthracite found in this field is normal in all characteristics, including a low ash-softening temperature range of between 2150 and 2530°F, with a corresponding tendency to clinker.

**West Virginia.** The U.S. Geological Survey map, "Coal Fields of the United States," shows deposits of anthracite coal west of Harrisonburg in Buckingham and Augusta Counties, and in Berkley County, West Virginia (west of Martinsburg).

### TRUE ANTHRACITES

The only commercial production of true anthracite in the United States is in the states of Pennsylvania and New Mexico. In addition, some true anthracite is located in Colorado, but it is not being mined to any extent at this time.

Of known reserves, Pennsylvania has over 98 per cent. In production, Pennsylvania as of 1940 shipped all but about 50,000 tons of true anthracite and all but 400,000 tons of all anthracitic coals in the United States.

For geographical reasons, the anthracites of Colorado and New Mexico are not competitive with Pennsylvania anthracite. Virginia semianthracite has been in competition as far north as Philadelphia. Pennsylvania anthracite and Pennsylvania semianthracite are competitive. Pennsylvania anthracite and Arkansas semianthracite are competitive in the St. Louis area.

**New Mexico.** New Mexican anthracite is mined in the small Cerrillos field of Santa Fe County. The coal is of good quality with 5.8 per cent volatile and 8.3 per cent ash. The ash-softening temperature is low.

Distribution is largely by rail to Arizona, California, Colorado, Kansas, Nebraska, New Mexico, Texas, and Wyoming.

**Colorado.** Colorado anthracite and semianthracite are found in the same fields. The analyses indicate a very satisfactory coal, with low to medium volatile, low ash, and high heat value.

The unfavorable points are a relatively low ash-softening temperature, with corresponding tendency to clinker; and the fact that both anthracite and semianthracites are found in the same location, which might lead to a variation in the quality of fuel obtainable from a given section.

**Pennsylvania.** Pennsylvania anthracite occurs in one region of approximately 500 sq miles in northeastern Pennsylvania. Four fields are recognized; the northern field, Lackawanna and Luzerne Counties; the eastern middle field, Luzerne and Carbon Counties; the western middle field, Northumberland, Columbia, Schuylkill, and Dauphin Counties.

With the possible exception of the practically unmined extreme western tips of the southern field, all coal mined in this region is true anthracite. (A more complete description of Pennsylvania anthracite is covered in the first part of this chapter.)



## CHAPTER 4

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### BITUMINOUS COAL, SUBBITUMINOUS COAL, AND LIGNITE<sup>1</sup>

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<sup>1</sup> See also Chap. 2 and sections on individual processes such as grindability and drying for the bulk of the information on bituminous coal.

## BITUMINOUS COAL<sup>1</sup>

Bituminous coal has been the industrial backbone of both the United States and Great Britain for over a century. In the United States, 28 states report total reserves of 1,330,000,000,000 net tons (Table 1-12). Reserves in these states range from a minimum of 100,000,000 net tons to Colorado with 212,000,000,000 net tons. By the latest and most conservative estimate (Chap. 1), this coal is sufficient to last for 681 years at present rates of consumption, even after it is assumed that coal will eventually be called upon to assume the roles now played by oil and gas.

**Classification of Bituminous Coal.** According to ASTM Standard specifications for the classification of coal (Table 2-1), which is the accepted standard of the industry, coals of true bituminous rank are divided into five groups according to either dry fixed carbon or moist Btu content as follows:

### II. Classification of Bituminous Coal:

1. Low-volatile: Dry fixed carbon 78 per cent or more and less than 86 per cent  
(Dry volatile matter 22 per cent or less and more than 14 per cent)
2. Medium-volatile: Dry fixed carbon 69 per cent or more and less than 78 per cent  
(Dry volatile matter 31 per cent or less and more than 22 per cent)
3. High-volatile A: Dry fixed carbon less than 69 per cent. Dry volatile more than 31 per cent. Moist Btu 14,500 or more<sup>2</sup>
4. High-volatile B: Moist<sup>3</sup> Btu 13,000 or more and less than 14,000<sup>3</sup>
5. High-volatile C: Moist Btu 11,000 or more and less than 13,000<sup>3</sup>

### Sizing and Selection of a Size of Bituminous Coal<sup>4</sup>

Because of the inherent differences in the fracturing characteristics and in local marketing conditions, screening and sizing practices vary widely in different fields.

In general, **bituminous coal sizes** are expressed as two numerals, both of which refer to the diameter of round-hole screens used in the sizing. The first, or larger, numeral refers to the size of screen through which the coal was passed, and the second, or smaller, numeral refers to the size of screen through which the coal would not pass. The use of only one numeral usually means that the coal contains all the components of the run-of-mine sizes which passed through the one screen mentioned; the use of a zero or such terms as "slack" in lieu of a second numeral has the same meaning. Thus the term 5 by 2-in. egg means that the coal passed through a 5-in.-round opening but was retained on a 2-in.-round-hole screen, the word "egg" being merely a trade term having, in the bituminous industry, no fixed meaning; while 2- by 0-in., or 2-in. nut slack means that the coal contains all the run-of-mine components below 2 in.

Since, from field to field, there are almost as many size designations as there are fractional screens, it is important to think in terms of size of bituminous coal, and size range, rather than in terms of names of sizes other than as represented by the accom-

<sup>1</sup> EDITOR'S NOTE: As much of this volume treats the properties, preparation, and use of bituminous coal, it was thought expedient to place most of the material on bituminous coal under individual subject headings, reserving only the very general material which could not otherwise be classified for this chapter. Examples of data on bituminous coal which will be found elsewhere are additional information on analyses, world supplies, characteristics, etc., in Chap. 2 by reason of not having been separated from coals of other ranks; grindability (pulverization) in Chap. 17; drying in Chap. 16; coke and coke making in Chap. 6; selection of bituminous coal; and all specific uses under the equipment involved.

<sup>2</sup> Moist Btu refers to coal containing its natural moisture but not including visible water on the surface of the coal.

<sup>3</sup> Coals having 69 per cent or more of fixed carbon on the dry mineral-matter-free basis shall be classified according to the fixed carbon regardless of Btu.

<sup>4</sup> Coal Bureau, Upper Monongahela Valley Association, *Reference Bulls.* 1 and 2, Fairmont, W. Va., and New York.

Table 4-1. Range of Analyses of Bituminous Coals Produced in the United States<sup>1</sup>

State and county	Bed	Rank <sup>a</sup>	Usual range of proximate analyses, per cent										Usual range heat value dry coal, Btu/lb		Usual range ash-softening temp, deg F	
			Dry coal (moisture-free)													
			As-received moisture		Volatile matter		Fixed carbon		Ash		Sulphur					
			Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
Alabama:	Yeshic	HV-A	1	4	35	37	61	55	4	10	0.6	1 2	13,800	14,600	2100	2400
Bibb	Thompson group															
Bibb	Clark															
Bibb	Youngblood															
Jefferson:																
Warrior field	Pratt	MV, HV-A	1	3	28	33	65	59	5	10	1 1	2 6	13,800	14,700	2300	2500
Warrior field	Mary Lee	MV, HV-A	2	3	26	31	62	56	10	15	0 7	1 5	13,000	13,900	2600	2900
Warrior field	Black Creek	HV-A	2	5	31	34	65	62	2	6	0 6	0 9	14,500	15,100	2500	2800
Walker	Mary Lee	HV-A	2	5	29	34	58	52	11	15	0 6	1 2	12,500	13,200	2600	2900
Arkansas:																
Logan	Paris	LV	1	2	17	19	75	69	8	11	1 7	2 6	13,700	14,400	2300	2500
Sebastian:	Hartshorne	LV	1	4	15	19	79	69	5	13	0 7	2 1	13,400	14,900	2100	2400
Colorado:																
Boulder	Uncorrelated		16	21	37	40	57	53	4	8	0 3	1 0	12,100	12,600	2000	2300
Herfano	Uncorrelated		3	8	36	42	53	48	8	14	0 5	1 0	12,200	13,200	2200	2700
La Plata	Uncorrelated		2	5	36	42	56	47	6	16	0 6	2 0	12,200	14,300	2600	3000
Las Animas	Uncorrelated		1	4	31	39	56	49	8	17	0 5	0 9	12,600	13,700	2300	2900
Moffat	Uncorrelated		11	22	36	43	58	50	3	9	0 3	1 1	11,900	13,100	2000	2400
Routt	Uncorrelated		7	14	37	43	57	51	3	8	0 4	1 0	12,300	13,500	2000	2800
Weld	Uncorrelated		20	26	37	40	58	53	4	9	0 3	0 8	11,900	12,700	2000	2300
Illinois																
Christian	Herrin (No. 6)	HV-C	12	14	40	42	47	44	12	15	4 4	5 5	12,000	12,500		
Franklin	Herrin (No. 6)	HV-B, C	7	11	34	39	56	52	8	12	0 6	1 5	12,800	13,400	2100	2500
Perry	Herrin (No. 6)	HV-C	8	12	37	39	53	47	9	15			12,000	13,100	2000	2300
St. Clair	Herrin (No. 6)	HV-C	7	11	37	44	48	43	10	18	3 6	4 8	11,700	12,700	2000	2200
Saline	Harrisburg (No. 5)	HV-B	5	8	35	38	56	53	7	11	1 9	3 3	13,000	13,600	2000	2100
Indiana:																
Knox	V (five)	HV-B, C	9	11	40	43	49	47	9	12	3 6	4 8	12,700	13,000	2000	2200
Pike	V (five)	HV-B, C	8	12	39	43	50	46	9	13	2 7	5 2	12,600	13,200	2000	2200
Warriack	V (five)	HV, B-C	7	12	39	43	49	46	9	13	3 6	4 4	12,600	13,100	2000	2200
Kansas:																
Crawford	Various in shale	HV-A	2	8	33	41	56	48	8	16	2 3	5 0	12,500	13,800	2000	2400
Kentucky:																
Bell	Mason	HV-A	2	4	36	40	59	55	3	7	0 8	1 3	13,900	14,600	2400	2600



Table 4-1. Range of Analyses of Bituminous Coals Produced in the United States. (Continued)

State and county	Bed	Rank <sup>a</sup>	Usual range of proximate analyses, per cent												Usual range heat value dry coal, Btu/lb		Usual range ash- softening temp, degf	
			Dry coal (moisture-free)								As-received moisture							
			Volatile matter		Fixed carbon		Ash		Sulphur		Low	High	Low	High				
			Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
Kentucky: (Continued)			Straight Creek	HV-A	2	4	37	41	59	55	2	6	0.6	1.5	14,200	14,800	2100	2300
Bell	.....	.....	Upper Elkhorn No. 3	HV-A	1	5	36	39	60	55	3	6	0.6	1.5	14,000	14,600	2200	2700
Daviess	.....	.....	Upper Elkhorn No. 2	HV-A	3	6	36	39	59	56	4	6	0.7	1.3	14,100	14,300	2200	2700
Floyd	.....	.....	Upper Elkhorn No. 1	HV-A	3	5	37	39	58	54	4	7	0.8	1.5	13,900	14,400	2300	2700
Floyd	.....	.....	High Splint	HV-A	2	5	37	40	57	56	3	7	0.5	1.0	13,700	14,300	2300	2700
Harlan	.....	.....	Keokee	HV-A	2	4	37	40	60	57	3	6	0.5	1.2	14,200	14,700	2200	2500
Hopkins	.....	.....	No. 11 western Ky.	HV-B	5	8	39	42	53	47	8	13	3.7	4.7	12,500	13,300	2000	2100
Hopkins	.....	.....	No. 9 western Ky.	HV-B	5	9	38	41	51	48	9	14	3.4	4.4	12,600	13,100	2000	2100
Knox	.....	.....	Dean	HV-A	3	6	37	39	56	53	6	0.8	1.2	13,600	13,900	2600	2900	
Letcher	.....	.....	Elkhorn	HV-A	2	4	36	39	61	56	2	6	0.5	1.7	14,300	14,700	2200	2800
Martin	.....	.....	Warfield	HV-A	2	4	39	41	54	51	6	9	1.4	2.8	13,600	14,000	2200	2600
Muhlenberg	.....	.....	No. 9 western Ky.	HV-B	5	9	38	41	51	48	9	13	3.3	4.5	12,700	13,200	2000	2100
Perry	.....	.....	Hazard No. 7	HV-A	3	6	36	38	58	55	5	8	0.6	0.8	13,700	14,100	2800	3000
Perry	.....	.....	Hazard No. 6	HV-A	4	6	35	38	58	55	6	9	0.6	0.9	13,400	13,900	2900	2900
Perry	.....	.....	Fire Clay No. 4	HV-A	3	5	36	40	58	54	4	7	0.7	1.2	13,900	14,500	2300	2800
Pike	.....	.....	Lower Elkhorn	HV-A	2	4	33	36	62	58	4	8	0.4	0.8	14,100	14,600	2600	3000
Union	.....	.....	No. 9 western Ky.	HV-A, B	3	7	37	40	52	48	9	14	3.3	4.2	12,700	13,400	2000	2100
Webster	.....	.....	No. 9 western Ky.	HV-A	3	6	36	39	52	49	9	13	3.5	4.3	12,900	13,300	2000	2100
Maryland:			Lower Sewickley	LV, MV	2	4	19	21	73	70	6	9	1.0	1.4	14,100	14,500	2700	2900
Allegany	.....	.....	Pittsburgh	LV	2	5	17	20	74	69	7	12	0.8	1.7	13,700	14,500	2700	3000
Montana:			Uncorrelated	Lignite	33	43	37	42	53	44	8	16	0.4	1.9	9,700	11,300	2100	2800
Eastern lignite field	.....	.....	Uncorrelated	HV-B, C	8	12	37	39	52	47	10	16	0.7	2.3	11,600	12,100	2100	2800
Red Lodge field	.....	.....	.....	.....	10	17	33	38	58	53	7	10	0.4	0.8	12,400	12,900	2200	2400
Roundup-Bull Mt. field	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	
New Mexico:			Raton	HV-A	1	3	34	38	52	47	11	15	0.6	0.9	12,800	13,400	2700	3000
Colfax	.....	.....	Uncorrelated	HV-A	9	16	39	46	53	45	5	13	0.4	1.2	12,200	13,500	2100	2800
McKinley	.....	.....	Middle Kittanning	HV-B	7	9	37	40	55	52	7	10	1.0	1.9	12,900	13,300	2400	2700
Ohio:			Pittsburgh	HV-A	2	4	39	43	51	48	7	11	3.5	4.8	13,100	13,700	1900	2100
Athens	.....	.....	Pittsburgh	HV-A	3	5	38	40	52	49	8	12	2.4	4.0	12,900	13,500	2100	2300
Belmont	.....	.....	Pittsburgh	HV-A	3	7	37	40	54	50	8	12	2.3	4.2	13,000	13,500	2100	2200
Harrison	.....	.....	Middle Kittanning	HV-B	7	10	37	42	53	49	7	11	1.0	3.5	12,700	13,200	2200	2700

Oklahoma:	Lower Hartshorne	1	5	16	20	77	72	6	11	0	7	1	6	13,700	14,700	2100	2400
LeFlore	McAlester	2	4	35	39	59	53	5	10	0	4	1	1	13,200	14,300	2000	2300
Oklmulgee	Pittsburg	2	5	38	40	56	52	6	8	0	5	2	3	13,800	14,200	2000	2200
Pennsylvania:	Lower Hartshorne	2	5	38	40	56	52	6	8	0	5	2	3	13,800	14,200	2000	2200
Allegheny	Pittsburg	2	5	34	38	58	53	5	10	0	8	1	3	13,500	14,300	2400	2700
Allegheny	Upper Freeport	1	4	32	38	59	53	5	12	1	2	4	4	13,300	14,300	2000	2700
Armstrong	Lower Kittanning	1	3	35	40	55	51	7	12	2	5	4	3	13,400	14,200	2100	2400
Butler	Upper Freeport	2	5	33	38	58	53	8	11	1	3	3	1	13,500	14,400	2100	2700
Cambria	Lower Freeport North	1	4	23	27	69	63	7	11	1	0	2	9	13,900	14,300	2200	2800
Cambria	Lower Freeport South	1	4	17	24	74	70	8	11	2	1	2	9	13,900	14,300	2200	2800
Cambria	Lower Kittanning	1	4	16	24	77	68	5	11	0	3	1	3	13,900	14,300	2200	2800
Clarion	Lower Freeport	1	4	23	27	70	64	6	11	0	9	2	6	13,800	14,600	2300	2900
Clarion	Lower Kittanning	1	4	21	26	70	64	7	13	0	3	3	6	13,600	14,400	2300	2900
Fayette	Sewickley	2	4	33	37	57	51	10	13	2	6	4	6	13,200	13,700	2200	2500
Fayette	Pittsburg	1	5	31	36	61	56	7	11	0	7	2	6	13,700	14,300	2300	2900
Fayette	Lower Kittanning	1	4	23	31	69	59	8	15	1	7	4	4	13,200	14,400	2200	2500
Greene	Pittsburg	2	4	35	37	58	54	7	10	1	3	3	3	13,700	14,100	2200	2400
Indiana	Upper Freeport	1	3	27	32	65	58	7	11	0	8	2	9	13,700	14,400	2200	2700
Jefferson	Lower Freeport	2	4	30	36	63	57	6	10	0	8	3	2	13,800	14,600	2200	2800
Somerset	Pittsburg	2	4	20	22	71	66	9	13	0	8	2	2	13,700	14,200	2500	2900
Somerset	Upper Freeport	1	4	18	22	72	67	8	13	0	8	2	5	13,500	14,300	2300	2900
Somerset	Lower Freeport	2	4	17	21	76	68	7	12	0	6	2	5	13,500	14,300	2500	2900
Somerset	Upper Kittanning	1	4	16	19	75	68	8	13	0	9	2	8	13,800	14,800	2300	2900
Somerset	Lower Kittanning	1	5	16	19	77	69	7	14	0	8	3	1	13,300	14,600	2300	2800
Washington	Pittsburg	2	5	34	40	58	50	6	12	0	8	3	6	13,000	14,200	2100	2600
Westmoreland	Upper Freeport	2	4	24	26	65	62	10	12	1	0	1	5	13,600	13,900	2600	2900
Westmoreland	Pittsburg, east	1	4	28	30	62	57	9	13	1	0	2	9	13,300	14,000	2400	2900
Westmoreland	Pittsburg, west	2	4	32	35	60	55	8	13	1	0	2	3	13,600	14,100	2500	2900
Westmoreland	Upper Freeport, east	2	3	22	27	65	61	11	13	1	0	4	0	13,300	14,200	2100	2500
Westmoreland	Upper Freeport, west	2	3	32	36	58	53	7	11	1	3	3	8	13,500	14,300	2000	2400
Tennessee:																	
Anderson	Big Mary	1	3	36	39	54	52	8	11	2	6	3	5	13,300	13,700	2200	2500
Anderson	Coal Creek	1	3	36	39	57	55	5	9	0	8	1	0	13,900	14,400	2200	2500
Campbell	Jellico	3	5	37	40	59	55	3	7	0	8	1	5	13,800	14,400	2300	2800
Claiborne	Jellico	2	5	35	39	59	56	3	9	0	8	1	6	13,700	14,600	2200	2600
Fentress	Wilder	1	4	35	38	54	51	9	12	2	8	3	5	13,200	13,600	2000	2300
Grundy	Sewanee	2	5	29	32	61	57	8	11	0	6	1	0	13,400	13,800	2300	2700
Morgan	Coal Creek	1	3	38	41	56	50	5	11	1	0	5	5	13,800	14,700	2000	2300
Overton	Wilder	2	4	35	38	55	51	9	12	2	5	3	5	13,200	13,600	2100	2400
Scott	Coal Creek	1	5	36	40	60	55	4	9	0	7	3	6	13,700	14,500	2200	2600
Utah:																	
Carbon	Uncorrelated	3	7	42	46	52	47	5	9	0	4	1	0	13,200	13,900	2100	2400
Emery	HV-B, C	3	5	41	45	52	48	5	8	0	5	0	7	13,200	13,900	-	-

Table 4-1. Range of Analyses of Bituminous Coals Produced in the United States. (Continued)

State and county	Bed	Rank*	Usual range of proximate analyses, per cent										Usual range heat value dry coal, Btu/lb		Usual range ash-softening temp, deg F	
			Dry coal (moisture-free)													
			As-received moisture		Volatile matter		Fixed carbon		Ash		Sulphur					
			Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
Virginia:																
Buchanan.....	Clintwood	HV-A	2	3	31	33	63	60	6	8	0.8	1.3	14,300	14,600	2600	3000
Buchanan.....	Lower Banner	MV	1	3	21	24	70	68	7	10	0.6	1.6	14,200	14,700	2600	2800
Dickenson.....	Upper Banner	MV, HV-A	1	3	29	33	66	60	5	7	0.6	1.0	14,500	14,800	2400	2800
Lee.....	Taggart	HV-A	3	4	36	40	60	56	3	7	0.4	0.8	13,800	14,500	2100	2500
Russell.....	Upper Banner	HV-A	2	4	35	37	59	57	6	8	0.4	0.9	14,200	14,500	2200	2500
Tazewell.....	Raven	HV-A	1	3	30	33	62	58	6	10	0.5	0.6	14,000	14,600	2200	2500
Tazewell.....	Pocahontas No. 3	LV, MV	1	4	19	23	77	72	4	6	0.4	0.8	14,800	15,200	2200	2600
Wise.....	Taggart	HV-A	1	3	35	37	63	59	2	4	0.5	0.8	14,800	15,100	2200	2500
Wise.....	Imboden	HV-A	1	3	34	36	61	57	5	8	0.6	0.9	14,100	14,500	2500	2900
Wise.....	Upper Banner	HV-A	1	3	32	36	61	57	5	9	0.5	0.9	14,100	14,600	2300	2700
Washington:																
Renton-Newcastle	Isaquah field	HV-B, sub B	9	19	38	42	50	44	8	19	0.3	1.2	10,900	12,800	2200	2900
Green River field	Eastern part	HV-A, B	3	6	33	37	50	42	14	22	0.6	1.0	11,400	12,400	2300	2900
Kittitas.....	Roslyn	HV-A, B	3	6	38	40	49	46	12	15	0.4	0.5	12,300	13,100	2300	2700
Kittitas.....	Uncorrelated	HV-A	3	5	34	39	52	45	13	19	0.3	0.6	12,100	13,000	2300	2700
Lewis, west	Uncorrelated		26	31	43	48	48	40	9	14	0.6	1.2	10,800	11,500	2100	2400
Pierce.....	Uncorrelated	HV-A	2	6	29	39	57	48	12	15	0.5	1.5	12,800	13,600	2300	2800
West Virginia:																
Barbour.....	Pittsburgh	HV-A	1	3	36	39	55	51	7	10	1.7	3.7	13,700	14,200	2000	2300
Brooke.....	Pittsburgh	HV-A	2	5	37	40	54	50	7	13	2.2	4.5	13,000	13,800	2000	2200
Fayette.....	Campbell Creek No. 2	HV-A	2	3	32	37	64	57	4	8	0.6	1.4	14,000	14,900	2300	2900
Fayette.....	Powellton	HV-A	1	3	32	35	64	60	3	6	0.6	0.9	14,500	15,100	2600	2900
Fayette.....	Eagle	MV, HV-A	1	4	28	33	66	58	4	9	0.6	1.7	13,900	14,800	2700	3000
Fayette.....	Sewell	MV	1	5	21	27	74	69	2	4	0.5	1.3	14,600	15,200	2200	2700
Fayette.....	Fire Creek	LV, MV	1	4	19	23	74	71	4	7	0.5	1.0	14,600	15,000	2300	2800
Greenbrier.....	Sewell	MV	2	5	25	27	70	68	4	6	0.8	1.4	14,600	14,900	2200	2500
Harrison.....	Pittsburgh	HV-A	1	3	38	42	55	50	6	10	1.7	4.3	13,600	14,300	2000	2300
Kanawha.....	Winfrede	HV-A	2	5	33	37	61	56	5	9	0.5	0.9	13,800	14,600	2600	3000
Logan.....	Chilton	HV-A	1	4	33	37	60	56	5	10	0.6	1.2	13,900	14,500	2500	2900
Logan.....	Cedar Grove	HV-A	1	4	33	39	59	54	5	10	0.6	1.8	13,700	14,500	2300	2900
Logan.....	Eagle	HV-A	2	5	32	36	63	57	4	8	0.6	1.1	14,000	14,600	2600	2900
Marion.....	Pittsburgh	HV-A	1	3	36	40	57	52	6	9	0.8	2.4	13,800	14,200	2100	2400
McDowell.....	Sewell	LV	1	3	17	20	77	73	4	8	0.5	0.8	14,600	15,000	2400	2800

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McDowell	Welch	LV	2	3	17	19	76	72	6	8	0.5	0.7	14,400	14,700	2500	2900	
McDowell	Beckley	LV	1	3	16	18	75	71	8	11	0.5	0.8	13,900	14,300	2300	2700	
McDowell	Pocahontas No. 4	LV	1	3	15	18	78	76	6	8	0.5	0.8	14,400	14,800	2100	2400	
McDowell	Pocahontas No. 3	LV	1	5	15	22	79	72	4	9	0.5	0.9	14,500	15,100	2200	2700	
Mercer	Pocahontas No. 3	LV	1	4	16	20	79	74	3	8	0.5	0.9	14,600	15,200	2400	2800	
Mingo	Winifrede	HV-A	2	5	36	39	57	53	6	9	0.6	1.0	13,600	14,000	2600	3000	
Mingo	Cedar Grove	HV-A	1	4	34	38	60	54	5	9	0.7	1.7	13,900	14,500	2300	2900	
Monongalia	Sewickley	HV-A	1	4	34	39	54	49	11	13	1.8	4	13,100	13,500	2100	2400	
Monongalia	Pittsburgh	HV-A	1	3	35	38	56	53	7	10	2.3	3	6	13,700	14,100	2100	2400
Ohio	Pittsburgh	HV-A	2	4	39	43	52	48	7	11	3.7	4.5	13,300	13,800	2000	2200	
Preston	Bakerstown	HV-A	1	3	28	31	64	61	6	10	0.9	1.9	14,000	14,600	2200	2500	
Preston	Upper Freeport	HV-A	1	5	27	32	62	55	9	16	0.9	4.1	13,000	14,100	2200	2800	
Preston	Lower Kittanning	MV	2	4	23	25	67	63	9	12	1.6	2.4	13,600	14,100	2400	2700	
Raleigh	Sewell	LV, MV	1	4	19	22	75	72	3	7	0.6	1.2	14,500	15,200	2300	2800	
Raleigh	Beckley	LV	1	4	16	19	79	74	2	8	0.5	1.0	14,500	15,200	2500	3000	
Raleigh	Fire Creek	LV	1	3	16	20	79	75	4	8	0.6	1.2	14,400	14,900	2400	2800	
Raleigh	Pocahontas No. 3	LV	1	3	15	18	79	74	5	9	0.6	1.0	14,300	15,000	2600	2900	
Randolph	Lower Kittanning	HV-A	1	4	29	31	61	57	9	13	1.0	2.6	13,400	14,000	2600	3000	
Randolph	Sewell	MV, HV-A	2	5	25	32	69	62	5	7	0.6	0.8	14,500	14,800	2500	2900	
Taylor	Pittsburgh	HV-A	1	3	37	40	55	52	7	9	2.3	2.8	13,900	14,300	2000	2300	
Wyoming	Sewell	MV	1	4	21	24	75	71	3	6	1.0	1.6	14,800	15,200	2300	2800	
Wyoming	Beckley	LV	1	3	18	20	77	73	4	7	0.8	1.4	14,500	15,100	2300	2800	
Wyoming	Pocahontas No. 6	LV	1	3	16	19	78	75	4	7	0.5	0.8	14,700	15,100	2500	2900	
Wyoming	Pocahontas No. 3	LV	1	3	16	19	78	74	5	9	0.5	0.9	14,300	14,900	2600	2900	
Carbon	Uncorrelated	HV-C, sub A or B	9	17	39	45	56	47	4	10	0.3	1.3	12,000	13,000	2100	2500	
Hot Springs	Uncorrelated	HV-C, sub A	11	15	38	42	57	52	4	9	0.6	1.1	12,500	13,300	2100	2300	
Sheridan	Uncorrelated	sub B or C	19	26	40	45	56	48	4	9	0.4	0.9	11,500	12,400	2100	2300	
Sweetwater	Uncorrelated	HV-B, HV-C, or sub A	6	14	41	43	55	52	3	6	0.9	1.1	12,800	13,700	2100	2300	

1 "Typical Analyses of Coals of the United States," U.S. Bur. Mines Bull. 446. See Table 2-1 for ASTM classification of bituminous coals by rank.

\* LV: low-volatile bituminous coal.

MV: medium-volatile bituminous coal.

HV-A: high-volatile A bituminous coal.

HV-B: high-volatile B bituminous coal.

HV-C: high-volatile C bituminous coal.

sub A: subbituminous A.

sub B: subbituminous B.

sub C: subbituminous C.

panying numbers. However, even this is not stable since, because of different characteristics of fracture, two coals of the same size range might have entirely different size consists; *i.e.*, of two 5- by 2-in. egg coals, one might contain a large percentage of 5-in. material and the other practically none. Table 4-2 shows the size consists of three common industrial and pulverizer sizes of a typical popular coal (Fairmont-Pittsburgh seam). Basic run-of-mine is also shown in Table 4-3.

Table 4-2. Typical Size Consist of Bituminous Coal<sup>1</sup>

Screen sizes	Coal sizes					
	2-in. nut and slack		¾-in. × 0 slack		¾-in. × 0 slack	
	Per cent	Cumulative	Per cent	Cumulative	Per cent	Cumulative
Round hole, in. diam:						
2	0	0				
1½	18 3	18 3				
1¼	8 7	27 0				
1	8 8	35 8				
¾	9 7	45 5	0	0		
½	9 9	55 4	18 1	18 1		
¾	6 3	61 7	11 8	29 9	0	0
U.S. Standard sieves:						
No. 4 (0.187 in.)	7 8	69 5	15 1	45 0	22 0	22 0
No. 8 (0.0937 in.)	10 5	80 0	18 2	63 2	26 0	48 0
No. 16 (0.0469 in.)	8 0	88 0	14 8	78 0	20 5	68 5
No. 30 (0.0232 in.)	5 0	93 0	9 5	87 5	13 8	82 3
No. 50 (0.0117 in.)	3 0	96 0	5 1	92 6	7 3	89 6
No. 100 (0.0059 in.)	1 7	97 7	3 1	95 7	4 4	94 0
No. 200 (0.0029 in.)	0 8	98 5	1 5	97 2	2 1	96 1
Passing No. 200	1 5	100 0	2 8	100 0	3 9	100 0

<sup>1</sup> Coal Bureau, Upper Monongahela Valley Association, *Reference Bull.* 2.

Table 4-3. Basic Run-of-mine Size Consist of Typical Bituminous Coal (Fairmont-Pittsburgh seam)

Size range, in.	Per cent	Cumulative per cent	Size range, in.	Per cent	Cumulative per cent
Above 5	18 4	18 4	1¼ × ¾	10 4	69 4
5 × 2	25 4	43 8	¾ × ¾	9 1	78 5
2 × 1¼	15 2	59 0	¾ × 0	21 5	100 0

**Use of Proper Size Important to Plant Performance.** Many performance difficulties are blamed on coal quality, which are in reality the result of an improper combination of coal sizing and equipment design or proportioning. Complaints such as excessive dust or fines, heavy coking or caking, poor air distribution, segregation, low grindability, high moisture, slagging, excessive fly ash, and clinkering can all be minimized or eliminated by the selection of the proper size of coal to be used or by the modernization of the equipment so that the natural and economical sizes can be satisfactorily handled and burned.

For example, it is seen in Table 4-2 that 20 per cent of 2-in. nut slack will pass through a No. 8 sieve (approximately a 1/10-in. round hole). This fine coal is high in heat value and will give economical and satisfactory results in a plant designed for the inclusion of this size. Nevertheless, the plant with a design weakness calls this fine

**Table 4-4. General Uses of Several Bituminous-coal Sizes**

<i>Nominal Size, In.</i>	<i>Most Common Use</i>
5 lump	Hand-firing, domestic and industrial
5 × 2 egg	Domestic hand-firing and gas producers
2 × 1¼ nut	Domestic hand-firing, industrial stokers, and gas producers
1¼ × ¾ stoker	Domestic and small industrial stokers
1¼ × 5/16 stoker	Domestic and small industrial stokers
¾ × ¾ stoker	Domestic and small industrial stokers
¾ × 0 slack	Industrial stokers and pulverizers
5/8 × 0 slack	Particularly suited to pulverizers
½ × 0 slack	Particularly suited to pulverizers
¼ × 0 slack	Particularly suited to pulverizers
1¼ × 0 nut slack	Industrial stokers
2 × 0 nut slack	Industrial stokers

coal "dust" or "dirt" and insists on the application of dustless treatments or selects the more costly double-screened coals from which the fines have been removed. The result is a limited coal selection, increase in cost, and decrease in availability.

As all manufacturers can furnish apparatus to utilize the best size values and the most economical and readily available coals, the desirable alternative would be to design the plant for the available coal rather than attempt to design the coal for the plant. Such measures as liberal designs for furnace volumes, grate area, grinding capacity, heat liberation, and coal flow will assure the widest latitude in selecting coals and sizes which will produce the lowest steam costs.

#### Commercial Sizing of British Coals<sup>1</sup>

British coal sizing is far from standardized. While their coal is known by such names as pearls, peas, beans, singles, and nuts, the names are used inconsistently, with the nuts of one colliery becoming the beans of another, etc. Furthermore, there is no sharp line of demarcation between the sizes. Table 4-5 thus refers to typical analyses rather than to accepted standards:

**Table 4-5. Typical Sizing of British Coals<sup>1</sup>**

	¼-0 in., per cent	½-¼ in., per cent	1-½ in., per cent	1½-1 in., per cent
Pearls	40	55	5	0
Peas	8	78	14	0
	10	65	25	0
Beans	8	53	39	
	6	41	53	0
Singles	6	30	60	4
	4	18	72	6

<sup>1</sup> BRITISH FUEL EFFICIENCY COMMITTEE, "The Efficient Use of Fuel," Chemical Publishing Company, Inc., Brooklyn, 1945.

Slacks usually contain all material below a specified screen, *i.e.*, single-screened. Slacks are also variously known as dross, smalls, duff, gum, etc., all according to the district of mining rather than the size. The upper size of British slack is frequently as large as 2 in. and as small as ⅜ in.

#### Geographic Variations in Coal Quality<sup>2</sup>

**Ash Content.** The percentage of ash is an extremely variable character and has no consistent relation to the rank of coal. It tends to vary not only from region to region

<sup>1</sup> BRITISH FUEL EFFICIENCY COMMITTEE, "The Efficient Use of Fuel," Chemical Publishing Company, Inc., Brooklyn, 1945.

<sup>2</sup> YOUNG, WILLIAM HARVEY, "Sources of Coal and Types of Stokers and Burners Used by Electric Public Utility Power Plants," Pamphlet Series, Vol. II, No. 2, Brookings Institution, Washington, D.C., 1930.

and from seam to seam but also from mine to mine and even in different parts of the same mine. Furthermore, it must be remembered that the ash content of delivered coal depends quite as much on care in preparation as on the character of the coal in the bed. In all the major districts of the country, increasing attention is being paid to the removal of impurities, and much of the tonnage is now subjected to cleaning processes. It is thus dangerous to generalize, as many local exceptions can always be taken.

Nevertheless, a close study of over 1,700 mine samples analyzed in the fuel-testing laboratories of the U.S. Bureau of Mines has shown some rather broad differences in ash content as between the different regions. In general, the coals of the Appalachians are somewhat lower in ash than those of the Interior fields. Of the Appalachian coals, those of the middle region are distinctly lower than those of the northern; in fact, the coals of the middle Appalachians average lower in ash content than any other of the great producing regions of the country. Of the Interior fields the coals of Illinois, Indiana, and western Kentucky average distinctly lower in ash than those of Iowa, Missouri, and Kansas, though a trifle higher than those of Oklahoma and Arkansas. Similar wide variations appear in other parts of the country. In Alabama and in the Rocky Mountain fields both high- and low-ash coals are found. The coals of the Pacific Coast are generally somewhat high in ash, the average of the car samples reported from the state of Washington being 14.5 per cent.

At the risk of injustice to individual coals, and thus with the further caution that an analysis is the only reliable guide, Table 4-6 shows the average ash content of

**Table 4-6. Average Percentage of Ash in Car Samples Arranged According to Origin**

Producing region	Number of samples	Average per cent ash (dry basis)
Northern Appalachian (Pennsylvania, Ohio, Maryland, northern West Virginia) <sup>a</sup> . .	528	10 2
Middle Appalachian (southern West Virginia, Virginia, eastern Kentucky)	845	7 2
Eastern Interior (Illinois, Indiana, western Kentucky) <sup>b</sup> . . . . .	198	11 9
Western Interior (Iowa, Missouri, Kansas). . . . .	64	15 2
Oklahoma, Arkansas . . . . .	107	11 7

<sup>a</sup> In calculating the average for the region as a whole, the simple arithmetical average for each state was weighted by the total tonnage produced in 1929.

<sup>b</sup> Includes in addition to the published analyses for Indiana and western Kentucky, samples of coal delivered from approximately 137 mines in Illinois.

several hundred samples from Eastern and Interior fields, arranged according to region. The figures represent the unweighted average of all analyses that had been published by the Bureau of Mines for the areas in question as of the date of publication, 1929. It should be noted that many more samples had been taken in some districts than others, and this may have affected the average.

**Mechanical Cleaning.** The ash content of delivered coal depends quite as much upon the care in preparation as upon the character of the coal in the bed. Increasing attention is being paid to the removal of impurities by either hand picking or mechanical cleaning by wet washing or pneumatic methods. Despite this interest, the 1946 U.S. Bureau of Mines "Minerals Yearbook" reports only 140 million tons out of a total of 532 million tons as cleaned mechanically in that year (less than 27 per cent). It must therefore be assumed that the quality of the coal underground in the various sections is in many cases indicative of the quality of delivered coal.

**Fusing Temperature of the Ash.** The national averages of ash-fusing temperature in the analyses made by the U.S. Bureau of Mines indicate much less variation within specific regions than the analyses of ash content (see Fig. 4-1). The Appalachian coals, on the whole, have high-fusion ash; with a few exceptions the ash of these coals fuses at 2200 to 2900°F and over. The fusing temperature of the ash from most Middle Western coal ranges from less than 2000 to 2199°F. There is a wide variation in the Rocky Mountain coals, some counties averaging as low as 2000°F while others are in the 2800 to 2899°F class. In all the counties of Washington, the average reported is more than 2200°F.

**Caking and Free-burning Coals.** The caking property does not lend itself to exact measurement, and coals range by imperceptible graduations from completely free-burning types that show no tendency to fuse in the furnace to mildly caking types

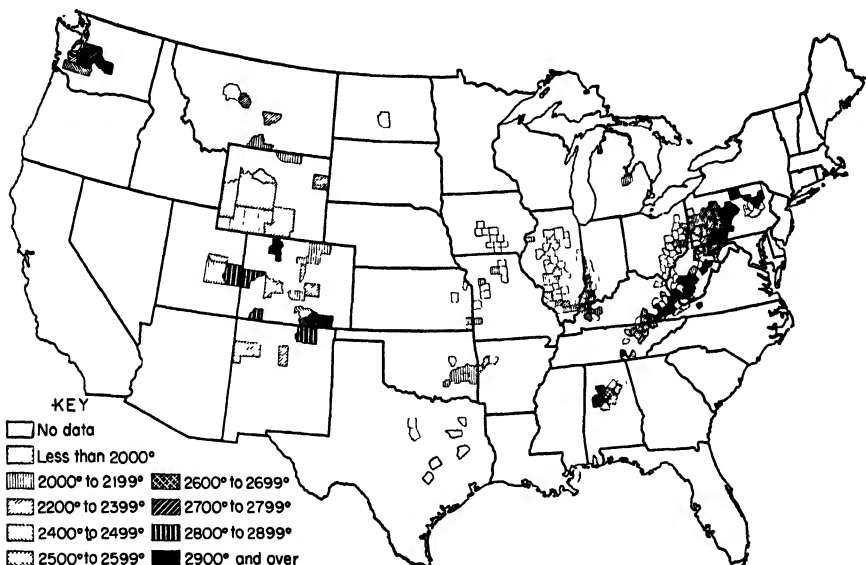


FIG. 4-1. Broad variations in fusing temperature of ash of coals of the United States. (William H. Young, "Sources of Coal and Types of Stokers and Burners Used by Electric Public Utility Power Plants," The Brookings Institution.)

that form a weak and friable crust and strongly caking types that fuse into solid masses of coke. The term "coking coal" is usually reserved for those coals capable of making a firm hard coke suitable for metallurgical use and is therefore of narrower application than "caking coal," which is used in general apposition to "free-burning."

Some idea of the geographical occurrence of the caking property is given by the map in Fig. 4-2. In it are shown the counties in which coal is now, or has been, mined for coke manufacture. The map shows strikingly that the caking tendency is most strongly developed in the great Appalachian region and that parts of Oklahoma, Washington, and the southern Rocky Mountains also produce strongly caking coals. In general, the coals of the Middle West and northern Rocky Mountains are free-burning. There are, however, numerous local exceptions. Even in the Middle West, there are coals that have been successfully made into coke, although none of them could be described as strongly caking.

In examining the map (Fig. 4-2), it must be remembered that a coal possessing the caking property to a moderate degree may never in fact be used in coke ovens, either



because it is too high in sulphur or other impurities or because other nearby coals are better adapted to the purpose. Thus, in many of the counties along the western border of the Appalachians, which appear white on the map, the coal mined is moderately caking and, were it not so near the highest grade caking coals of the country, might be sought for coke manufacture.

**Heating Value of Bituminous Coal.** There are wide variations in the heating value of the different coals of the United States. In general, the coals of the Appalachians

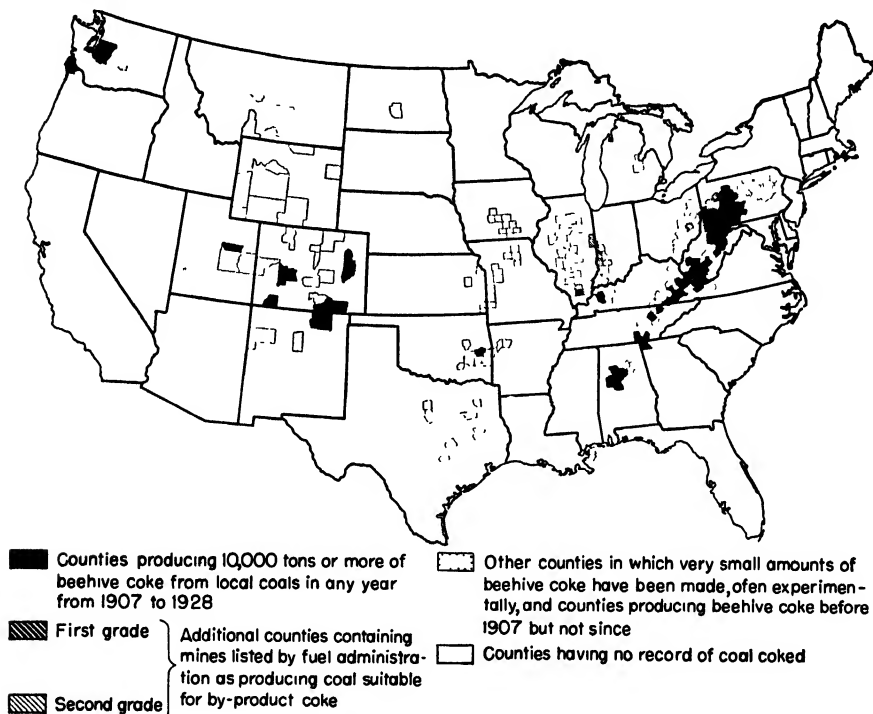


FIG. 4-2. Counties now producing coking coal, or which have produced in the past. (William H. Young, "Sources of Coal and Types of Stokers and Burners Used by Electric Public Utility Power Plants," *The Brookings Institution*.)

and of Arkansas and Oklahoma are higher in Btu than the coals of Middle West and Rocky Mountain region.

Though there is no direct relation between the heating value of coal and the type of stoker used, the heating power has a decided influence on the distance which the coal can be shipped and on its ability to penetrate certain markets. The high-Btu coals of the Appalachian region move much greater distances than low-Btu coals of other sections. Pocohontas-New River coals are shipped to 20 states for power generation; the lignite from Texas does not leave the state.

#### Quality of Middle Western Bituminous Coals<sup>1</sup>

Much of the Middle Western bituminous coal seems to have been profoundly affected in the southern reaches by the diastrophism of the Ozark region, *i.e.*, by the upheaval and folding of the mountains by forces which compressed the coal in the

<sup>1</sup> OLIN, H. L., Iowa Coals in the National Emergency, *Mech. Eng.*, May, 1943, pp. 343-346.

seams near the center of disturbance to semianthracite, but which only to a lesser degree hardened and chemically altered others along a wide radius. This is clearly shown by the results of Campbell's work plotted as Fig. 4-3 obtained from studies of mine moisture contents of coals sampled over a large area. Thus it appears that mine moisture, and with it certain chemical and physical properties affecting the storability and other characteristics of coal, varies as some function of the distance from this active center.

Moisture contents of the fuels from the so-called "quality circle" of southern Illinois, Indiana, and Kentucky range between 5 and 10 per cent; those of north and central Illinois and of Iowa, having missed the natural processing and refining of the more southerly coals, carry moisture values of 12 to 20 per cent. Further, because the

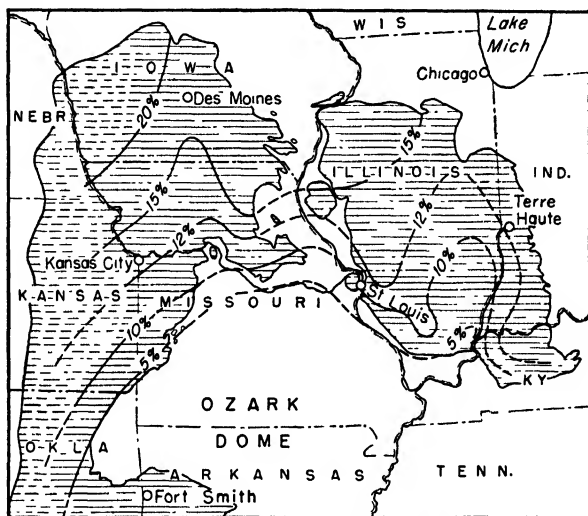


FIG. 4-3. Campbell's lines of equal moisture values for Middle Western coals. (H. L. Olin, *Mechanical Engineering*, May, 1943.)

seams are thinner and smaller, costs of mining and preparation are higher and, because they were laid down in areas less favorable to natural coal-formation processes, they suffer somewhat in quality comparison with others in this general region.

#### Plastic Properties of Bituminous Coals<sup>1</sup>

Plasticity and the closely related property of some coals, expansion upon heating, are of interest to coke-oven operators. Certain coals expand to an extent that makes them dangerous to charge into coke ovens alone. In some instances, such coals may be mixed with contracting coals to form a safe resultant.

Because there is considerable divergence of opinion concerning the measurement of plasticity of homogeneous materials, the measurement of the plasticity of coal, a most heterogeneous material, is a most difficult one. Three methods of test have been suggested but as yet none is considered standard: (1) resistance to gas flow test, wherein the flow of gas through coal as it is raised in temperature gives an indication of plasticity; (2) swelling test (Agde-Damm), in which the linear expansion of small briquettes as heated to 500°C is measured to give the "swelling coefficient" and "free expansion swelling coefficient"; and (3) the plastometer test, as developed by J. D.

<sup>1</sup> MALLEIS, O. O., in "Symposium on Significance of Tests of Coal," *Trans. ASTM*, vol. 37, 1937.

Davis, U.S. Bureau of Mines, in which a continuous measurement of the viscosity of coal is made while it is being heated through the plastic state. The resistance to gas flow test is also known as the "Layng and Hathorne test."

**Table 4-7. Agglutinating Values for Straight Bituminous Coals<sup>1</sup>**

(Arranged according to volatile matter)

Coal No.	State	County	Bed	H <sub>2</sub> O, per cent	Dry basis, per cent		Btu dry ash-free, per cent	Agglutinating value	
					V.M. <sup>a</sup>	Ash		Crushing strength, kg	Coal-sand ratio
23	W.Va.	McDowell	Pocahontas 4	0 8	15 5	4 8	15,750	16 3	1:10
26	W.Va.	Raleigh	Sewell	1 3	21 1	2 1	15,720	9 7	1:15
								5 6	1:20
								3 3	1:25
4	Md.	Garrett	Davis	1.4	22 4	9.9	15,560	12 2	1:10
27	W.Va.	Fayette	Sewell	1 9	27 0	2 4	15,640	7 6	1:15
								4 8	1:20
								2 9	1:25
11	Canada	British Columbia	B	1 4	27 4	6 3	15,410	14 6	1:10
7	Ala.	Jefferson	Mary Lee	1 2	28 2	16 1	15,200	11 3	1:10
8	Ala.	Jefferson	Mary Lee W	4 2	28 8	8 7	15,490	13 0	1:10
17	Ala.	Jefferson	Pratt	1 5	30 6	9 3	15,380	12 7	1:10
31	Va.	Buchanan	Clintwood	1.9	32 1	5.7	15,520	8 3	1:15
								4 4	1:20
								2 9	1:25
18	Ala.	Jefferson	Pratt W	3 0	32 5	3 2	15,450	9.9	1:10
12	Pa.	Fayette	Pittsburgh	1 0	33 9	8 6	15,270	9 7	1:10
9	Pa.	Fayette	Pittsburgh	1 9	34 3	7 6	15,350	10 9	1:10
1W	Pa.	Allegheny	Pittsburgh W	2 4	35 3	6 0	15,170	9 7	1:10
1	Pa.	Allegheny	Pittsburgh	1 6	34 8	7 6	15,190	6 7	1:10
10	Ill.	Franklin	No. 6	7 9	34 9	13 4	14,460	4 3	1:10
28	Pa.	Allegheny	Pittsburgh	1 8	35 7	5 6	15,240	7 6	1:15
								5 3	1:20
								3 3	1:25
3	Va.	Wise	Taggart	1 7	36 7	2 7	15,450	5 7	1:10
14	W.Va.	Logan	Chilton	2 2	37 0	4 4	15,190	8 4	1:10
20	Pa.	Allegheny	Thick Freeport	2 2	37 1	6 4	15,160	10 2	1:10
13	Ala.	Walker	Black Creek	3 1	37 2	2 7	15,050	6 7	1:10
2	Ky.	Letcher	Elkhorn	2 2	37 4	2 2	15,070	4 3	1:10
22	W.Va.	Marion	Pittsburgh	1 9	38 0	6 1	15,210	13 3	1:10
16	W.Va.	Boone	Alma	2 1	38 5	7 3	15,210	9 3	1:10
15	W.Va.	Kanawha	No. 2 Gas	1 9	39 6	2 8	15,150	7 1	1:10
21	Ky.	Muhlenberg	Green River	10 1	40 3	7 5	14,400	8 6	1:10
19	Utah	Carbon	Lower Sunnyside	4 6	40 7	6 3	14,570	3 9	1:10
32	Pa.	Washington	Pittsburgh	2.0	42.1	8 2	14,810	7 8	1:15
								5 1	1:20
								3 2	1:25
								2 3	1:30

<sup>1</sup> U.S. Bureau of Mines Monograph 5, and Papers 570, 571.

<sup>a</sup> Volatile matter.

Although plasticity and expansion, reduced to dependable measures, offer promise for predicting coking and stoker results, information is meager, with the experience of the coke operators being the best guide to coals currently available.

#### Gas- and Coke-making Properties of Bituminous Coals<sup>1</sup>

In the testing of coal for the manufacture of coke, nearly all the yield data and characteristics of the various products can be fairly satisfactorily determined by

<sup>1</sup> MALLEIS, O. O., *loc. cit.*

Table 4-8. Agglutinating Values for Mixed Bituminous Coals<sup>1</sup>

Coal No.	Kind of coal	H <sub>2</sub> O, per cent	Dry basis, per cent		Btu dry ash-free, per cent	Agglutinating value	
			V.M. <sup>a</sup>	Ash		Crushing strength, kg	Coal-sand ratio
18A	80 % No. 17 (Pratt), 20 % No. 7 (Mary Lee)	3 4	29 2	6 4	15,520	10 1	1:10
17	100 % Pratt	1 5	30 6	9 3	15,380	12 7	1:10
7	100 % Mary Lee	1 2	28.2	16 1	15,200	11 3	1:10
5	40 % No. 1 (West Pittsburgh), 60 % No. 4 (Davis)	1 5	28.1	7 6	15,460	11 6	1:10
6	80 % No. 1 (West Pittsburgh), 20 % No. 4 (Davis)	1 3	33 7	5 5	15,240	10 6	1:10
1W	100 % Pittsburgh West	2 4	35 3	6 0	15,170	9 7	1:10
4	100 % Davis	1.4	22.4	9.9	15,560	12.2	1:10
30	80 % No. 28 (Pittsburgh), 20 % No. 27 (Sewell)	1 9	34 3	4 8	15,340	7 8	1:15
28	100 % Pittsburgh	1 8	35.7	5 6	15,240	7 6	1:15
27	100 % Sewell	1 9	27.0	2 4	15,640	7 6	1:15
29	80 % No. 22 (Pittsburgh), 20 % No. 26 (Sewell)	1 8	32 6	4 9	15,330	8 2	1:15
22	100 % Pittsburgh	1 9	38 0	6 1	15,210	13 3	1:10
26	100 % Sewell	1.3	21 1	2 1	15,720	9 7	1:15
24	80 % No. 22 (Pittsburgh), 20 % No. 23 (Pocahontas)	1 3	32 9	6 0	15,270	10 2	1:10
22	100 % Pittsburgh	1 9	38 0	6 1	15,210	13 3	1:10
23	100 % Pocahontas No. 4	0 8	15 5	4 8	15,750	16 3	1:10

<sup>1</sup> U.S. Bur. Mines Monograph 5.<sup>a</sup> Volatile matter.

laboratory or small-scale tests, except the physical characteristics of the coke which may be produced in a coke oven.

**High-temperature coking tests include:**

1. *Laboratory Distillation Tests.* The procedure most generally used is the "tube test" as published by the Chemists Committee of the U.S. Steel Corp.<sup>1</sup> In this test, 20 g of 35-mesh dry coal are heated progressively to 900°C or higher under prescribed conditions. The tube test gives the yields of coke, gas, tar, ammonia both free and fixed, light oil, and the calorific value of the gas may be obtained from the sample.

2. *Carbonization Test.* In the Bureau of Mines-American Gas Association tests, unquestionably the best large-scale carbonizing procedure, from 85 to 175 lb of coal may be carbonized in retorts ranging from 13 to 18 in. in diameter and at temperatures of from 500 to 1100°C. Sufficient yields of all products are obtained for any desired analytical examination, a most desirable feature.

In comparison with plant practice, yields at the proper carbonizing temperatures were surprisingly close, except that ammonia yields are low because of decomposition in the iron retort.

3. *Box-coking Tests.* Box-coking tests are made in regular ovens and are usually for the purpose of obtaining information about the physical character of the coke. For this purpose they rate next to full-scale oven tests for reliability of results.

Summarizing the three methods of testing: (1) the tube test is usually sufficient for yield data and calorific value of the gas produced, (2) the BM-AGA carbonization test permits an examination of the various products of carbonization, and (3) the box-

<sup>1</sup> "Sampling and Analysis of Coal, Coke, and By-products," 3d ed., p. 130, U.S. Steel Corp., 1929.

coke tests are best for a determination of the physical quality of the coke. Naturally, final confirmation in full-oven tests is the ultimate guide.

**Low-temperature Coking Test.** In the Fischer low-temperature assay, the usual laboratory test for the evaluation of coals for low-temperature coking, 50 g of coal are distilled at 500°C. In commenting on this test, the U.S. Bureau of Mines (*Monograph 5*) says in part:

The tar yield obtained in low-temperature plants usually is about 70 per cent of the Fischer assay yields because of decomposition of part of the primary air in the retort. The assay is useful for indicating the theoretical yields of liquid by-products on low-temperature distillation. As to tar yield, it indicates the characteristics of the coal rather than results to be expected from the retort or coke oven.

### Caking Properties of Bituminous Coals<sup>1</sup>

The term "coking" or "caking" property is very general and hard to define properly. As usually interpreted, strongly coking or caking means: (1) on industrial stokers, a coking or matting over of the fuel bed which cannot be readily broken up by the normal operation of the stoker; (2) on residential stokers, the formation of coke trees which materially disturb the fuel bed; and (3) in a coke plant, the production of a coke of a desired size which will stand the necessary mechanical handling without the production of excessive coke breeze.

Most coals, when heated at a uniformly increasing temperature in the absence of air, fuse and become plastic. Fieldner and Selvig have designated such coals as caking coals, and they point out that coals possess this property in varying degrees.

Two methods are being used for testing or determining the caking properties of coals:

**Coke Button from the Volatile-matter Test.** The examination of the coke button resultant from the standard volatile-matter test has long been used as a first step in an estimation of the caking properties of coals. Although this is the simplest of all coking tests, an interpretation of results has to be based mainly upon a visual examination of the coke button. Furthermore, as various authorities have pointed out, close standardization of testing conditions is necessary in order to secure comparable results. Nevertheless, though the results are by no means infallible, they do serve as an important aid to distinguishing among noncaking, poorly caking, or strongly caking coals. In general, the following will serve as a guide to a very rough interpretation of coke-button formations:

Low-volatile coals, when heated in the standard volatile-matter test, usually expand to many times the volume of the original coal used for the test, and often the resulting coke button will completely fill the test crucible. The fairly strong coking high-volatile coals generally fuse quite completely and form more or less spherical coke buttons, often several times the size of the original volume of the test coal, with some coke buttons from the most strongly coking high-volatile coals as large as one-half the volume of the test crucible. Weakly caking coals do not expand to any extent, and their resulting coke button will occupy about the same volume as the coal used for the test. The coke buttons from the very strong coking coals are very porous and usually contain a fairly large cavity in the central portion. The coke buttons from the more poorly coking coals usually are denser, since these coals do not swell to any extent upon the application of heat in the volatile-matter test. Usually the central portions of the coke button from a poorly caking coal have "dropped," and there are one or more decided fracture cracks across and through the coke button. In noncaking coals there is practically no fusing together of the coal particles, and the residue from heating is still in either the granular state or will fall apart on the application of slight pressure.

**Agglutinating-value Test.** Agglutinating values for coals may be obtained by crushing buttons made by carbonizing mixtures of 45- to 60-mesh Ottawa sand and

<sup>1</sup> MALLERIS, O. O., *loc. cit.*, pp. 402-415.

0- to 200-mesh coal in a standard furnace under prescribed conditions. The tests are made to sand-coal ratios of 15:1, 20:1, 25:1, and 30:1.

An examination of the agglutinating values of a large number of coals as reported by the U.S. Bureau of Mines failed to reveal any definite trends of relationships, as a result of mixing coals of different indexes. Individual coals of approximately the same index also varied widely in the stability of the coke produced. These deviations are of a sufficient magnitude to invalidate the numerical agglutinating index at a single ratio as being a reliable indicator of the strength or stability of the coke that can be produced. It has thus been concluded that the agglutinating-value test seems to have little value as a reliable index of the probable caking or coking properties of a coal.

On the other hand, the agglutinating-value test has been found to have value for special investigations such as detecting the deterioration of coking properties of coal due to storage. In one series of tests, the agglutinating values were much more significantly affected by oxidation in storage than were the proximate or ultimate analyses, or the calorific values.

### SUBBITUMINOUS COAL AND LIGNITE

**Classification of Subbituminous Coal and Lignite** (see Table 2-1 for full classification of coals by rank). The ASTM classification of coals, accepted as standard by the industry, divides subbituminous coals into three classes or groups and lignite into two as follows:

III. Subbituminous Coal (both weathering and nonagglomerating):

1. Subbituminous A: Moist Btu 11,000 or more and less than 13,000<sup>1</sup>

2. Subbituminous B: Moist Btu 9,500 or more and less than 11,000<sup>1</sup>

3. Subbituminous C: Moist Btu 8,300 or more and less than 9,500<sup>1</sup>

IV. Lignite:

1. Lignite. Moist Btu less than 8,300. Consolidated

2. Brown coal. Moist Btu less than 8,300. Unconsolidated

The low-rank coals, subbituminous and lignite, containing 10 to 50 per cent natural bed moisture, represent over half of the all-rank coal-tonnage reserve of the United States, but only about 2 per cent of the United States coal production is derived from these fuels. Increased utilization of these large reserves awaits the perfection of a high-speed low-cost process for removing the bed moisture at the mine.<sup>2</sup>

**Subbituminous.** In the subbituminous ranks, approximately 7,500,000 tons are mined annually in Colorado, Wyoming, and Montana, of which approximately 50 per cent reaches domestic consumers. In areas where subbituminous coal is so used,

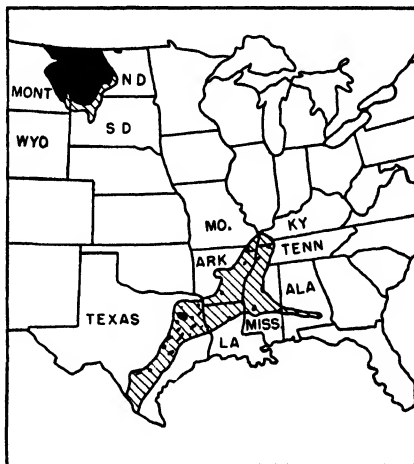


FIG. 4-4. Location of the more extensive lignite deposits in the United States. Solid area equals areas of proved commercial value. Shaded area shows regions of more doubtful commercial value. (U.S. Bureau of Mines, Bull. 255.)

<sup>1</sup> Moist Btu refers to coal containing its natural moisture but not including visible water on the surface of the coal.

<sup>2</sup> PARRY, V. P., J. B. GOODMAN, and E. O. WAGNER, Drying Low-rank Coals in the Entrained and Fluidized State, *Mining Trans. AIME*, April, 1949, p. 89.

it is considered to be a good domestic fuel; it is smokeless in most furnaces and has thus been used for many years in hand-fired domestic furnaces employing the large-lump method of firing.<sup>1</sup>

**Lignite.** Lignite is currently mined in the states of North Dakota, Texas, South Dakota, and Montana to the total extent of some 2,668,000 net tons (see Table 4-9). Of this amount over 2,500,000 tons, or 94.5 per cent, is mined in North Dakota.

**Table 4-9. Production of Lignite in 1945<sup>1</sup>**

	<i>Net Tons</i>
Montana <sup>a</sup> . . . . .	41,579
North Dakota . . . . .	2,522,319
South Dakota . . . . .	24,445
Texas . . . . .	79,949
Total . . . . .	2,668,310

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946. Exclusive of small mines producing less than 1,000 tons. (Such mines produced 22,644 tons in 1944.)

<sup>a</sup> Includes output from Custer, Dawson, McCone, Richland, Roosevelt, and Sheridan Counties.

Lignite does not differ much from subbituminous coal except for additional moisture (up to 50 per cent and even more), and the problems of utilization are about the same. Therefore, much of the data developed for subbituminous coals are equally useful for interpretation of lignite utilization.

An interesting factor in connection with the production of lignite is the ease with which it can be mined as compared with most other coals. In 1945, 74 per cent was recovered in strip mines, with an average daily production per miner of 14.26 net tons.<sup>2</sup> The average mine value in 1945 was \$1.55 per net ton.

Because of the difficulties of storing and shipping, most lignite is used in areas close to the mines. In 1945, the West North Central states consumed 668,636 tons of lignite in generating electric energy (Federal Power Commission).

**General Characteristics.** The moisture content of both subbituminous coal and lignite is high, averaging about 25 per cent as mined for subbituminous and considerably more for lignite. The coals are noncoking and slack to a variable degree when exposed to normal atmospheric conditions. The ash content ranges from 4 to 6 per cent, with a fusion temperature of about 2000°F.<sup>3</sup>

**Friability and slacking** both vary widely for subbituminous and lignite. In one series of tests,<sup>4</sup> friability ranged from 16.1 to 37.7 per cent (ASTM method); slacking or weathering indexes ranged from 29.2 to 73.0 (Pittsburgh index) and from 26.2 to 66.1 (trommel screen, 40 revolutions of trommel for 1 min).<sup>4</sup>

When such coals are exposed to the weather, they lose moisture rapidly. If evaporation from the surface of a lump proceeds at a faster rate than that at which it is replaced by moisture from the interior, the rate of shrinkage at the surface is greater than that at the interior; consequently, stresses are generated at the surface that cause the coal to disintegrate. Likewise, when moisture is absorbed by the air-dried surface, the outer layers expand at a faster rate than the interior, which results in further breakdown. As these cycles are repeated, the lump may disintegrate completely. Therefore, successful storage of low-rank coals depends on control of the factors that influence change in the moisture.<sup>5</sup>

**Spontaneous Combustion.** Subbituminous coal or lignite, when stored in random piles or in ordinary bins in which the temperature fluctuates and air circulates quickly, undergoes physical and chemical changes which decrease the utilization value of the

<sup>1</sup> Performance of Subbituminous Coals in a Typical Underfeed Domestic Stoker, *U.S. Bur. Mines Repts. Invest.* 3557, April, 1941.

<sup>2</sup> PARRY, GERNES, WAGNER, GOODMAN, and KOTH, Gasification of Lignite and Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 4128, September, 1947.

<sup>3</sup> PARRY, LANDERS, and GOODMAN, Automatic Water Heating Utilizing Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 3890, June, 1946.

<sup>4</sup> PARRY, V. F., and J. B. GOODMAN, Subbituminous Coals of the Denver Region, *U.S. Bur. Mines Repts. Invest.* 3457, August, 1939.

<sup>5</sup> PARRY, V. F., and J. B. GOODMAN, Storage of Subbituminous Coal in Bins, *U.S. Bur. Mines Repts. Invest.* 3587, October, 1941.

fuel and cause it to ignite spontaneously. The heating value is decreased, and slackening takes place.<sup>1</sup>

**Storage of Subbituminous.** In general, therefore, the same rules and cautions apply as for the storage of bituminous coal but to an even greater degree (see Chap. 18). In addition, the Bureau of Mines cautions that subbituminous and lignite should never be stored in piles higher than 10 ft (*Inform. Circ.* 7214).

Two additional methods are suggested for storing low-rank coals: (1) in earthen pits in which only the top surface is exposed to the weather and (2) completely under water. In any event, the coal pile *must* be as airtight as possible.

Table 4-10. Analyses of Subbituminous Coals from Denver Region, Colorado<sup>1</sup>

Mine	Sample No.	County	Bed	Con- dition <sup>2</sup>	Analysis, per cent											Btu per lb coal	Soft- ening temp of ash, deg F	Sub- bitu- minous rank
					Proximate					Ultimate								
					Moisture	V.M. <sup>3</sup>	Fixed C	Ash	H <sub>2</sub>	C	N <sub>2</sub>	O <sub>2</sub>	S					
Puritan	1	Weld	Unnamed	a	24 1	29 1	42 7	4 1 6 3	55 0	1 2 33	1 0 3	9,460	2050	B				
Van Winkle	2	Jefferson	Unnamed	b	24 4	38 3	56 2	5 5 4 8	72 4	1 6 15	3 0 4	12,470						
Baum	3	Weld	Unnamed	a	25 5	43 2	51 2	5 6 4 8	68 9	1 1 19	1 0 5	11,800	2420	C				
				b	25 5	28 8	42 2	3 5 6 5	54 3	1 2 34	2 0 3	9,320						
Gorham	4	Boulder	Gorham	a	19 6	38 7	56 7	4 6 4 9	72 9	1 6 15	6 0 4	12,520	2340	B				
				b	19 6	30 5	45 9	4 0 6 0	58 8	1 3 29	6 0 3	10,130						
Cap Rock	5	Jefferson	Laramie	a	25 3	37 9	57 1	5 0 4 8	73 1	1 6 15	2 0 3	12,600	2100	B				
				b	25 3	29 6	40 3	4 8 6 3	52 8	0 8 34	1 1 2	9,060						
Leyden	6	Jefferson	Leyden	a	39 7	53 9	6 4 4 7	70 7	1 0 15	6 1 6	12,140	2340	B					
				b	21 3	32 4	43 0	3 3 6 2	56 6	0 9 32	6 0 4			9,710				
Clayton	7	Weld	Unnamed	a	41 1	54 8	4 1 4 9	71 9	1 1 17	5 0 5	12,340	2390	B					
				b	22 8	30 0	42 2	5 0 6 2	55 3	1 2 32	0 0 3			9,550				
Pike View	8	El Paso	Fox Hills	a	38 9	54 6	6 5 4 8	71 5	1 6 15	2 0 4	12,360	2030	B					
				b	24 9	31 8	39 2	4 1 6 4	51 7	0 7 36	9 0 2			8,710				
Centennial	9	Boulder	Unnamed	a	42 4	52 1	5 5 4 8	68 9	0 9 19	6 0 3	11,600	2360	C					
				b	20 3	30 5	45 4	3 8 6 1	58 3	1 2 30	3 0 3			9,990				
Monarch	10	Boulder	Monarch	a	38 3	57 0	4 7 4 9	73 2	1 5 15	3 0 4	12,540	2120	B					
				b	20 4	30 2	45 2	4 2 6 2	57 9	1 2 29	9 0 6			9,980				
Bohlender	11	Weld	Unnamed	a	37 9	56 8	5 3 5 0	72 8	1 5 14	7 0 7	12,540	2210	B					
				b	33 4	25 5	36 5	4 6 6 8	46 9	1 0 40	4 0 3			8,070				
Comet	12	Weld	Comet	a	38 2	54 9	6 9 4 7	70 4	1 4 16	1 0 5	12,100	2170	C					
				b	33 3	25 9	34 9	5 9 6 8	45 8	0 9 39	7 0 9			7,860				
Premier	13	Boulder	Unnamed	a	38 8	52 4	8 8 4 6	68 6	1 4 15	3 1 3	11,780	2100	C					
				b	19 9	33 1	42 5	4 5 6 1	56 8	1 1 31	0 0 5			9,720				
Lewis	14	Boulder	Unnamed	a	41 3	53 0	5 7 4 9	71 0	1 3 16	5 0 6	12,150	2030	B					
				b	18 6	31 4	46 3	3 7 6 1	60 1	1 1 28	4 0 6			10,390				
				b		38 6	56 8	4 6 5 0	73 8	1 3 14	5 0 8	12,780	2320	B				

<sup>1</sup> U.S. Bur. Mines Repts. Invest. 3457, August, 1939.

<sup>2</sup> a: As-received basis. b: Moisture-free basis.

<sup>3</sup> Volatile matter.

**Size Consist of Subbituminous.**<sup>2</sup> It is estimated that in 1948 about 27 per cent of the northern Colorado subbituminous coal mined was crushed; approximately 74 per cent  $2\frac{1}{2}$ -in. slack, from which stoker sizes will be prepared and industrial fuel furnished. This shows a marked increase in the production of slack since 1935. The demand for industrial slack is increasing, and slack smaller than  $2\frac{1}{2}$  by 0 in. is suitable, permitting the removal of the more profitable prepared sizes for domestic use. The average size consist of samples studied shows that about 85 per cent of the slack can be screened into sizes containing no  $\frac{1}{8}$ -in. material and that about 41 per cent can

<sup>1</sup> PARRY, V. F., and J. B. GOODMAN, Storage of Subbituminous Coal in Bins, U.S. Bur. Mines Repts. Invest. 3587, October, 1941.

<sup>2</sup> PARRY, V. F., and W. S. LANDERS, U.S. Bur. Mines Repts. Invest. 3655, August, 1942.



be prepared as  $\frac{1}{4}$ - by 1-in. (square-hole) stoker coal, or 29 per cent  $\frac{3}{4}$ - by  $1\frac{1}{2}$ -in. round-hole (modified pea).

**Density.** The average bulk density of 16 subbituminous coals (Denver region) slack was 48.9 lb per cu ft; the average bulk density of clean fractions prepared by screening these samples averaged 40 lb per cu ft. Small particle density is 78 lb per cu ft.

**Specific Gravity.** Average apparent specific gravity of subbituminous coal in the northern Colorado field is 1.29 and ranges from 1.22 to 1.35.

**Specific heat** is about 0.50.

**Thermal conductivity** is 0.25 Btu/hr/deg F.

**Table 4-11. Typical Ultimate Analysis and Other Characteristics of North Colorado Subbituminous Coal<sup>1</sup>**

Ultimate analysis, per cent:	
Hydrogen .....	6 1
Carbon .....	56 1
Nitrogen .....	1 2
Oxygen .....	30 4
Sulphur .....	0 5
Ash .....	5 7
Total .....	100.0
Proximate analysis, per cent:	
Moisture ..	22 0
Volatile matter ..	29.7
Fixed carbon ..	42 6
Ash ...	5.7
Total ..	100.0
Physical properties:	
Ash-softening temp, deg F ..	2110
Heat value as received, Btu per lb ..	9550
Bulk density, lb per cu ft ..	42
Friability, per cent ..	25
Slacking index ..	50
Apparent specific gravity ..	1 29

<sup>1</sup> PARRY, LANDERS, and GOODMAN, Automatic Water Heating Utilizing Subbituminous Coal, U.S. Bur. Mines Repts. Invest. 3890, June, 1946.

**Application to Small Stokers.** Studies of the combustion of subbituminous coal and lignite in various appliances have revealed the advantages of the high reactivity natural to these fuels and illustrated the possibility of burning them in small stokers at very satisfactory efficiencies. Because these fuels will remain ignited while immersed in ash, a fuel bed will retain its fire or live coals until virtually all the carbon has been consumed. For example, it has been demonstrated that subbituminous coal will remain kindled in an open fireplace basket grate for 72 hr or even more. This property of high reactivity appears to be characteristic of all coals having more than 15 per cent natural bed moisture.

**Fine fly ash** is characteristic of subbituminous coal or lignite, because much of the carbon is burned at temperatures below the ash-fusion temperature; and, in most hand-fired appliances, no clinker forms. However, when burning these fuels in conventional stokers at high rates, clinker will form, but in most cases the fine ash is still blown around the firebox and is deposited in thick layers on all flat surfaces. Therefore, flat surfaces should be avoided when furnaces are designed for low-rank fuels.<sup>1</sup>

**Long banking periods**, described in the next paragraph, also react to the advantage of subbituminous coals stoker-fired. In one instance, a stoker using anthracite had to be operated continuously because the banking period was too short to hold the fire;

<sup>1</sup> PARRY, LANDERS, and GOODMAN, Automatic Water Heating Utilizing Subbituminous Coal, U.S. Bur. Mines Repts. Invest. 3890, June, 1946.

on subbituminous coal, the banking period was 200 min, permitting intermittent operation. (This was a small 7-in. retort, and the results are therefore indicative of relative banking but not conclusive as to performance on larger heating stokers.)

**Burning Characteristics of Low-rank Coals.** Although the standard appliances for burning coal will handle subbituminous coal with little difficulty, certain design features should be changed to take advantage of the special properties of high-moisture fuels. For example, deep fuel beds are not necessary when operating on lignite because the reducing action in the fuel bed occurs at much lower temperatures than is common with the high-rank fuels, and considerable combustible gases may be lost if insufficient secondary air is supplied. Furthermore, the high reactivity and relatively lower heating value make it necessary to tend the fire at more frequent intervals than is practiced when burning higher grade coals. The air supply to furnaces using low-rank coal is important because the fuel bed will consume any air that can come into contact with carbon, and it is desirable to have good control over air that is admitted to the fuel bed.<sup>1</sup>

**Low-temperature Carbonization.** Parry<sup>2</sup> describes experiments with the low-temperature carbonization of Colorado subbituminous coals which produced (1) a reactive char, amounting to approximately one-half the weight of the original coal and having a heating value of about 13,500 Btu per lb; (2) 3 to 9 per cent of tar oils; (3) 26 to 31 per cent of condensable water; and (4) 450 to 1,430 Btu in gas per lb of coal, depending on the temperature of carbonization.

**Table 4-12. Analyses of Various Lignites and Calculated Yields of Char (Residue) on Carbonization<sup>1</sup>**

Source of lignite	Lignite					Char free of volatile matter (moisture-free), per cent		
	Proximate analysis, per cent				Heating value, Btu	Fixed carbon	Ash	Yield
	Mois- ture	Volatile	Fixed carbon	Ash				
Texas	35 3	36 3	20 9	7 5	7,903	73 6	26 4	28 4
	32 8	37 1	22 9	7 2	7,763	76 1	23 9	30.1
	29 9	51 0	10 0	9 1	7,929	52 4	47 6	19.1
North Dakota	40 0	26 5	26 7	6 8	5,935	79 7	20 3	33.5
	30 3	30 3	32 3	7 1	7,165	82 0	18 0	39.4
	32 5	28 0	33 5	6 0	7,005	84 8	15 2	39 5
Colorado.	35 0	27 4	30 2	7.4	6,982	80 3	19 7	37.6
Arkansas	39 4	26 5	24 4	9 7	6,350	71 5	28 5	34 1
Alaska	38 2	23 8	22.2	15 8	5,263	58 5	41 5	38.0
	23 2	37.6	35.0	4.2	8,883	89 3	10.7	39.2

<sup>1</sup> "Investigations of the Preparation and Use of Lignite," p. 86, *U.S. Bureau of Mines*, 1918-1925.

**Carbonizing a Subbituminous Coal.<sup>3</sup>** Because of their general properties, it is not likely that low-rank coals will be carbonized in a coke oven, but different methods of processing must be developed to treat them. These coals lend themselves to continuous treatment in vertical retorts or in rotary retorts where the coal is heated to

<sup>1</sup> PARRY, LANDERS, and GOODMAN, Automatic Water Heating Utilizing Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 3890, June 1946.

<sup>2</sup> PARRY, V. F., and J. B. GOODMAN, Subbituminous Coals of the Denver Region, *U.S. Bur. Mines Repts. Invest.* 3457, August, 1939.

<sup>3</sup> DAVIS, J. D., and V. F. PARRY, Carbonizing Properties of a Subbituminous Coal from Puritan Mine, Weld County, Col., *U.S. Bur. Mines Repts. Invest.* 3248, February, 1939.

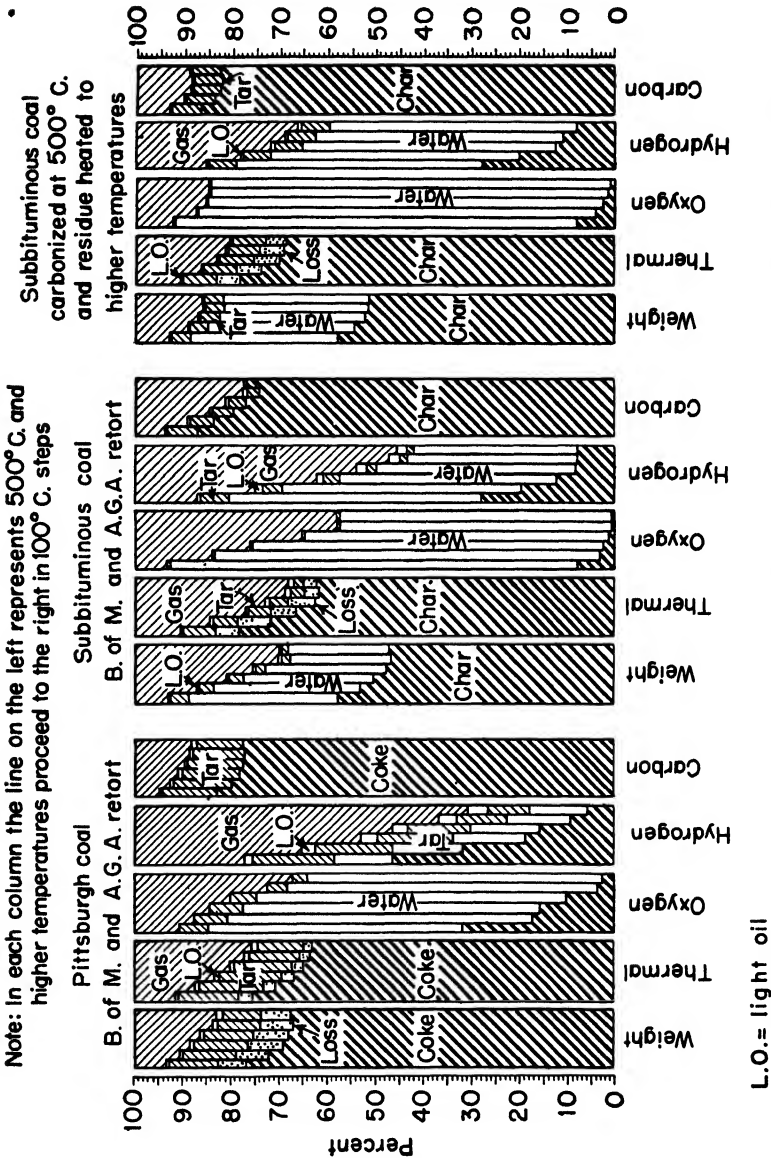


FIG. 4-5. Distribution of products from coal when carbonized at various temperatures. (U.S. Bureau of Mines, Rept. Invest. 3428.)

higher and higher temperatures while in motion and the volatile products are removed from the retort at their temperature of formation. Under such condition of heating, the secondary reaction or cracking of the tars and gases would not occur to the same extent as in the coke oven.

Experimental results on a typical subbituminous coal (Puritan Mine, Dacono, Weld County, Colorado) showed marked differences in properties as compared with similar results on a typical coking coal from the Pittsburgh seam in the same apparatus. The comparison is made by means of the bar chart shown as Fig. 4-5. The chart on the left represents the distribution of products from the Pittsburgh coal at various temperatures. The bars at the left in each column show the distribution at 500°C, and adjoining bars to the right are 600, 700, 800, 900, and 1000°C. The distribution of heat recovered and materials is thus shown on five bases, thermal, weight, oxygen, hydrogen, and carbon. The middle chart represents the results from subbituminous coal, and the chart on the right is the distribution of products from the same coal when secondary water-gas reactions are eliminated. A study of this figure will reveal the characteristic differences between a noncoking coal and a typical coking coal when carbonized by external heat. The length of the white bars emphasizes the great difference in yield of water. The decrease in the length of the white bar on the subbituminous chart as the temperatures increase gives a picture of the extent of the water-gas reaction.

**Briquettes from Subbituminous Coal.** The U.S. Bureau of Mines conducted experiments to compare briquettes from subbituminous coal with those from Pocahontas.<sup>1</sup> Generally speaking, it was found that subbituminous briquettes were inferior to those from the higher rank bituminous coal. There was a tendency to slack and to disintegrate in the fuel bed. About 2 per cent more binder was required for briquettes considered even passable; even so, completely satisfactory briquettes could not be made with subbituminous coal, even when binder concentrations were as high as 10 per cent.

**Table 4-13. Comparative Properties of Subbituminous Briquettes<sup>1</sup>**

(All briquettes made with an 8 per cent asphalt binder)

Briquette made from	Age, days weathering	Property		
		Strength	Sp gr	Abrasion resistance
Raw subbituminous coal (25 per cent moisture) . . . .	0	670	1 14	19
	25	225	1 06	64
Steam-dried subbituminous coal (6 per cent moisture) .	0	416	1 05	48
	28	224	1 04	79
Air-dried subbituminous coal (10 per cent moisture) .	0	764	1 07	41
	28	146	1 05	69

<sup>1</sup> PARRY, V. F., and J. B. GOODMAN, Briquetting Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 3707, June, 1943.

Steam drying stabilized the briquettes somewhat but imparted no significant improvement in physical properties. Btu content was 12,200 for steam-dried coal; 10,900 Btu from raw coal.

All subbituminous briquettes disintegrated somewhat while burning, because this fuel has no coking properties. High concentrations of binder do not overcome this undesirable property with either subbituminous or lignite.

<sup>1</sup> PARRY, V. F., and J. B. GOODMAN, Briquetting Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 3707, June, 1943.

Table 4-13 is presented for purposes of comparing briquettes made from three raw coals. In using this table, it is of interest to compare the results with the following tentative standards for satisfactory commercial pillow-shaped briquettes:

1. Compressive strength made through parallel surfaces on pillow-shaped briquettes should be at least 650 to 700 psi.
2. The apparent specific gravity, measured by weighing a paraffin-coated briquette in water, should be about 1.20.
3. The abrasion resistance, measured by material passing a 0.263-in. square-hole screen after five briquettes are tumbled for 1,200 revolutions in the ASTM apparatus for tumbler test for coal, should not be more than 25 to 30 per cent.

**Gasification of Lignite.**<sup>1</sup> Experimental work carried on by the U.S. Bureau of Mines at Grand Forks, N.D., in an externally heated (Parry) retort, showed that various grades of water gas having  $H_2:CO$  ratios of 2.1:5.4 could be readily produced by adjustment of temperature and concentration of steam. These gases were made at rates ranging from 65 to 80 cu ft/hr/sq ft of heated surface when employing a reaction zone 3 in. wide. The rate of gas formation or the rate of heat transfer in the annular retort is approximately inversely proportional to the width of the reaction zone. The indicated over-all efficiency of gasification was 72 per cent when it is assumed that producer gas and steam for the process can be generated at efficiencies of 80 and 85 per cent, respectively. As this work was purely experimental, the results shown may be subject to considerable modification as the project advances to the commercial stages.

<sup>1</sup> PARRY, GERNES, WAGNER, GOODMAN, and KOTH, Gasification of Lignite and Subbituminous Coal, *U.S. Bur. Mines Repts. Invest.* 4128, September, 1948.

## CHAPTER 5

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### PEAT, WOOD, WOOD WASTES, CHARCOAL, AND AGRICULTURAL WASTES

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## PEAT<sup>1</sup>

Peat, or "turf," is a decaying vegetable matter, disintegrated wholly or in part, usually brown in color and of a fibrous character. Although it is not recognized as one of the ranks of coal, it is convenient to designate peat geologically as the first step in the formation of coal beds, the sequence being growing vegetation, peat, lignite, subbituminous coal, bituminous coal, semianthracite, anthracite, and meta-anthracite or graphite. There are many kinds of peat grading from incipient decay to the loosest of lignite structure.

In the United States, peat is primarily used as a fertilizer. The familiar form is the bagged "humus," as it is called by the fertilizer companies. Peat also serves as a raw material for the manufacture of paper stock. Alcohol has been made from it. It has antiseptic properties and has been used for hygienic purposes, notably for wound bandages. Peat is found in abundance in the New England states, New York, Michigan, Wisconsin, Minnesota, and along the northern border of the states of New Jersey, Ohio, Indiana, Illinois, and Iowa. Peat seldom occurs in coal regions.

In central Canada there are no coal beds but an abundance of peat bogs. The Canadian government has thus made a sustained effort to find a place for peat to give Canada an independent fuel supply.

In Europe, especially Ireland, Scandinavia, and Russia, peat is a staple fuel.

Peat bogs constitute an enormous potential fuel reserve. However, as peat comes from the bog, it contains from 85 to 90 per cent water, which lowers its heat content to below 1,300 Btu; this water must thus be evaporated from peat before it can be used as a fuel. Because of its low heating power, peat is seldom used in its natural form where coal is procurable at reasonable prices; however, widespread attempts have been made to briquette peat so as to upgrade its value. Some of these have been very successful from mechanical and physical viewpoints, but most have met economic difficulties, again because of the cost of properly disposing of the water content.

### Classification of Peat

In all cases the disintegration of vegetable matter forming peat has occurred under water. It is necessary for peat formation that there be an area of depression, having a clay bottom whereon still water lies, favorable to the growth of aquatic and other plants. What are known as "high bogs" are principally made up, as far as their peat content is concerned, of the remains of mosses, moor plants, and forest residue. The vegetable matter forming the "low bogs" is usually composed of grass sedge and weeds. Bogs may consist of mixtures of the two genera of plants. Botanically speaking, the following subdivisions of the plants usually occurring in peat formations has been by J. Hallmén of Markaryd, Sweden:

#### Moss Peat.

a. *Sphagnum peat*, made from sphagnum moss, is difficult to dry, is very light, and is well adapted to the moss-litter industry and for bandage purposes.

b. *Hypnum peat* is rich in lime and nitrogen and is better suited to fertilizer than to fuel purposes, although it does not absorb moisture to the great extent common to the sphagnum peats.

c. *Forest-moss peat* consists largely of forest residues and when properly treated can be made into excellent fuel.

<sup>1</sup> STILLMAN, ARTHUR L., "Briquetting," pp. 184-187, Chemical Publishing Company, Inc., Easton, Pa., 1923.

### Grass Peat.

*a. Sea peat*, made from the remains of low-order ocean weeds, makes excellent fuel when properly disintegrated and treated.

*b. Carex-peat* plants are usually the product of sandy soils; therefore, there may be a considerable admixture of silts and sand, resulting in high ash content. Some bogs of this class, however, have delivered excellent fuel.

*c. Eriophorum*, or *cotton-grass peat*, has the best raw material for the manufacture of peat fuel when the contents of the bog have been well disintegrated. When not disintegrated, the fiber is strong, and attempts have been made to make fabric therefrom.

Another classification is that cited by S. W. Johnson:

*a. Turfy Peat*. Yellowish brown in color, spongy and elastic, but slightly decomposed

*b. Fibrous Peat*. Brown in color, less elastic, but with the fibers of vegetation easily distinguishable

*c. Earthy Peat*. Without fibrous structure, being an earthlike mass; breaks with some difficulty

*d. Pitchy Peat*. Dense and black with a lustrous fracture.

In this division, class *d* would be expected to operate in a manner similar to lignite, and class *a* would be more valuable for purposes other than fuel.

### Chemical Composition and Analysis of Peat

The chemical composition of peat is complex. Peat originates from cellulose or

**Table 5-1. Typical Proximate Analysis of Peat**

	As received, per cent	Dry basis, per cent
Moisture	91 02	0
Fixed carbon	3 00	33 41
Volatile matter	5 37	59 80
Ash	1 61	6 79
Sulphur	0 11	1 22

**Table 5-1a. Typical Ultimate Analysis of Peat**

	Per Cent
Carbon .....	58
Oxygen .....	35
Hydrogen ..	5 7
Nitrogen ..	1 2

vegetable substance and lignin or woody matter. These compounds are formed of carbon, oxygen, and hydrogen. Mixed therein are more complex compounds, resins, fats, and proteins. During the decomposition that results in peat, the humic, ulmic, and like acids are formed. The cellulose seems to be the least disturbed of the vegetable compounds concerned. Bitumen is common to all classes of peat. The decomposition is accompanied by a gas formation, in which are included carbon dioxide, methane, ammonia, and hydrogen sulphide.

While analyses of peat vary widely, a typical proximate analysis of a high-grade peat is given in Table 5-1.

Table 5-4 shows the variations and averages of a large number of analyses of dried peat from various countries.

### Dopplerite

This is a variety of peat, found chiefly in Styria but also occurring elsewhere in Europe, whose composition shows it to be highly acid. An analysis by Schrotter shows that it contains carbon, 48.06 per cent; hydrogen, 4.98 per cent; oxygen, 40.07 per cent; nitrogen, 1.03 per cent; and ash, 5.86 per cent.

It is amorphous and in the fresh state is elastic like rubber. Its luster is greasy,



Table 5-2. Analyses and High Heat Values of Air-dried<sup>a</sup> Peat<sup>1</sup>

Kind of peat	Locality	Constituents, per cent			High heat value, Btu/lb	
		Moisture <sup>a</sup>	Ash	Sulphur	Air-dried <sup>a</sup>	Moisture-free
Brown, fibrous . . . . .	Hamburg, Mich.	7 50	6 55	0 28	9,090	10,026
Light brown, fibrous . . . . .	Rochester, N.H.	11 64	4 06	0 22	9,083	10,280
Dark brown . . . . .	Westport, Conn.	12 70	4 12	0 24	8,590	9,839
Brown, structureless . . . . .	New Durham, N.H.	6 06	17 92	0 88	7,947	8,460
Brown . . . . .	New Fairfield, Conn.	9 63	7 93	0 46	7,861	8,698
Brown, fibrous . . . . .	Westport, Conn.	19 69	3 23	0 19	7,691	9,578
Brown, fibrous . . . . .	Cicero, N.Y.	14 75	7 42	0 25	7,576	8,869
Brown . . . . .	Black Lake, N.Y.	8 68	16 61	0 99	7,522	8,237
Salt marsh . . . . .	Kittery, Me.	13 50	12 04	1 94	7,319	8,462
Black . . . . .	Greenland, N.H.	6 62	24 11	1 01	7,186	7,695
Brown, fibrous . . . . .	Madison, Wis.	6 99	18 77	0 38	6,943	7,628

<sup>1</sup> U.S. Bureau of Mines.

<sup>a</sup> While moisture contents "air-dried" are as shown by U.S. Bureau of Mines, the peats as found contained from 85 to 95 per cent water. A very extensive drying is therefore indicated to bring the analyses down to these relatively low figures.

Table 5-3. Miscellaneous Properties and Characteristics of Peat

Color . . . . .	Variable, light brown through black
Weight . . . . .	Dry weight 7 to 60 lb/cu ft
Specific gravity:	
Air-dried . . . . .	0.7-1.1
Briquetted . . . . .	1.15-1.25
Bulk compared with coal . . . . .	8-18 times for same evaporating effect
Burning characteristics . . . . .	Easily kindled, burns freely, quick heat
Rate of formation in bogs . . . . .	Probably averages about 1-ft a century

Table 5-4. Range of Analyses of Peats from Various Countries<sup>1</sup>

	Variations, per cent	Avg per cent
Carbon . . . . .	37 15-66 55	53 83
Hydrogen . . . . .	4 08-10 39	5 97
Oxygen . . . . .	18 59-42 63	33 12
Nitrogen . . . . .	0 77- 3 10	1 34
Fixed carbon . . . . .	10 39-33 91	23 59
Volatile matter . . . . .	43 38-73 60	60 18
Ash . . . . .	1 05-32 95	9 58
Sulphur . . . . .	Usually below 1% but often as low as 0.1%, and sometimes higher than 1% in pyritiferous types	
Btu . . . . .	5,500-10,000 in air-dried samples	

<sup>1</sup> MOORE, E. S., "Coal," John Wiley & Sons, Inc., New York, 1940.

and its specific gravity is 1.089. It burns with little or no flame and omits an odor like peat.

### Methods of Preparing Peat for Fuel

In general, the methods used for preparing peat fuel are as follows:

#### 1. Cut Peat.

*a. By hand*, as in Ireland and Europe. Peat, cut with a tool known as a "slane," is stacked for air drying to about 30 per cent moisture. Drying racks or sheds are sometimes used. Bricks are about 9¼ by 4 by 4.

*b. By machine*, in effect briquetting machines in which the peat is first shredded and then reformed into cubes.

About 10,000,000 tons are so produced annually, mostly in Russia and Scandinavia. Unless extensive drying is employed, cut peat is of low heat value with much smoke.

**2. Briquetted Peat.** The peat is usually sun-dried to about 45 per cent, mechanically dried to some 30 per cent, and then briquetted on piston or roll briquette presses to a final moisture content as low as 12 to 6 per cent.

**3. Wet Carbonizing.** Peat under some 8 atm of pressure is heated in retorts to 150°C. The resultant hot water chars the peat, preparing it as a material suitable for subsequent briquetting.

**4. Peat Charcoal.** Methods range from crude charcoal burners of the conventional type to complete coking processes such as the "Ziegler," which distills off all by-products to leave a peat coke having about 88 per cent fixed carbon, 9 per cent volatile, 3 per cent ash, and 14,200 Btu per lb.

**Table 5-5. 1940 to 1946 World Production of Peat<sup>1</sup>**  
(In metric tons)

Country <sup>a</sup>	1940	1941	1942	1943	1944	1945	1946
Canada: Fuel	27	322	156	709	584	107	132
Peat moss	15,591	25,222	48,540	58,386	72,979	76,170	79,060
Denmark	2,500,000	4,700,000	4,800,000	6,200,000	5,800,000	5,685,000	3,700,000
Ireland	3,624,250 <sup>c</sup>	5,398,274	4,312,738	4,954,895	5,302,477	5,086,734	<sup>d</sup>
Finland..	13,716	10,982	8,659	2,364	2,840	7,280	<sup>d</sup>
France	23,880	83,560	209,740	190,210	112,619	92,000	78,000
Hungary	10,290	11,720	16,710	28,640	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Iceland	24,344	18,003	<sup>d</sup>	11,560	11,973	11,000	10,500
Italy	9,433	19,510	134,463	59,204 <sup>e</sup>	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Netherlands	616,640	748,810	712,935	648,800	535,550	386,050	571,940
Norway	<sup>d</sup>	127,000	185,000	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Sweden: Fuel	76,367	248,297	637,568	978,269	810,000	1,150,000	703,000
Litter, baled	123,201	118,599	112,400	110,000	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Litter un- baled	6,000	3,649	2,060	1,395	107,000	100,000	106,000
Baled	25,543	26,420	14,987	15,948	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Switzerland..	12,000	40,000 <sup>f</sup>	200,000 <sup>f</sup>	430,000 <sup>f</sup>	310,000 <sup>f</sup>	497,429	100,000
U.S.S.R. <sup>g</sup>	31,800,000 <sup>f</sup>	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>	19,760,000 <sup>f</sup>	<sup>d</sup>
United States <sup>h</sup>	64,000	78,000	65,000	54,000	88,000	97,000	127,647

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, Peat Preprint, p. 4, 1946.

<sup>a</sup> In addition to countries listed, Argentina, Austria, Germany, and Poland produce peat, but data of production are not available.

<sup>b</sup> Figures for 1940 to 1942 relate to production by holders of agricultural land only; those for 1943 to 1946 cover total production.

<sup>c</sup> Fiscal year ended Apr. 30 of year stated.

<sup>d</sup> Data not available.

<sup>e</sup> January to June, inclusive.

<sup>f</sup> Estimate.

<sup>g</sup> Excluding Estonia, Latvia, and Lithuania.

<sup>h</sup> Data for 1940 to 1943 are as reported to the Bureau of Mines by producers and probably represent only about two-thirds of total production. Data for 1944 to 1945 have been revised to provide estimates believed to represent, as does 1946, reasonably complete coverage.

## WOOD

### CORDWOOD<sup>1</sup>

Until about 1890, cordwood was the predominant fuel of the United States; whereas as late as 1875 nearly 3 cords of wood were used for each ton of coal mined. While this relationship, of course, declined steadily after this date, current demands for such purposes as fireplaces, rural and farm heating, tobacco curing, and other agricultural processing are still sufficiently great to make the annual production of cordwood roughly equal to that of Pennsylvania anthracite. Furthermore, although the volume of high-grade timber is decreasing year by year, inferior, waste, and thinned wood is sufficiently plentiful to supply all purposes without using wood that could be converted to lumber.

<sup>1</sup> Fuel Wood Used in the United States 1630-1930, *U.S. Dept. Agr. Circ. 641*, February, 1942. "Wood Fuel in Wartime." *U.S. Dept. Agr. Farmers Bull. 1912*, 1942.

### *Advantages of Cordwood*

1. Wood is clean to handle and free from disagreeable dust; it produces little smoke or soot when properly burned.
2. A cord of hardwood leaves a maximum of only about 60 lb of ashes; while a ton of anthracite will leave 200 to 300 lb, without including unburned combustible in the ash.
3. Wood ashes have a definite fertilizing value. (Anthracite ash is also admixed with soil, but its action is one of lightening rather than fertilizing.)
4. Wood has a low ignition temperature so that it is easy to start and can be maintained at a low rate of combustion.
5. Thinning and removing dead and stunted wood is beneficial to growths of timber, thus providing the owner with a convenient source of fuel from material which would otherwise be wasted.
6. Most people appreciate the pleasant aspect of a glowing open fire, especially in mild weather when relatively small amounts of heat are required.

### **Location of Hardwoods**

About one-fourth of the total volume of hardwoods is located in New England and the Middle Atlantic states. The Lake states contain nearly 12 per cent of the hardwood volume, and five Central states, Ohio, Indiana, Illinois, Iowa, and Missouri, have 8 per cent. Thus these three regions, where fuel consumption is heavy, have approximately 45 per cent of the hardwood stands of the nation.

**Table 5-6. Leading Fuel Woods by Regions, 1630 to 1930<sup>1</sup>**

New England	Middle Atlantic	South Atlantic	Lake
Oaks Maple Birch Pines Beech Hickory	Oaks Maple Birch Pines Beech Hickory	Pine (yellow) Oaks Hickory Gum Maple Ash	Oaks Maple Tamarack Aspen Birch Pines
Central	East Gulf	Lower Mississippi	Prairie
Oaks Maple Pine (yellow) Birch Hickory Beech	Pine (yellow) Oaks Hickory Gum Ash Chestnut	Pine (yellow) Oaks Gum Hickory Ash Maple	Oaks Cottonwood Hickory Maple Ponderosa pine Walnut
North Rocky Mountains	South Rocky Mountains	North Pacific	South Pacific
Ponderosa Douglas fir Lodgepole pine Aspen or cottonwood Larch	Juniper Piñon Aspen Ponderosa pine Oaks	Douglas fir Ponderosa pine Larch Oaks Alder	Oaks Ponderosa pine Douglas fir Redwood Eucalyptus

<sup>1</sup> Fuel Wood Used in the United States, 1630-1930, *U.S. Dept. Agr. Circ.* 641.

In all regions, the choice of wood for fuel is determined primarily by availability and ease of production and secondarily by heating value and lack of objectionable qualities. However, the manner in which this has worked out in actual practice is indicated in Table 5-6, listing the fuels used in each region in the order of accumulated volume used to date. In each region, the first three kinds named would probably include 80 per cent or more of the volume of fuel wood used throughout the regional history.

### Measurement of Cordwood

Stacked wood occupying 128 cu ft of space makes up 1 cord, usually considered as a pile 4 by 4 by 8 ft. The content of solid wood in a cord varies considerably, depending on the length, size, and form of the individual sticks as well as the care in fitting them together, but a fair average is 80 cu ft of solid wood to the cord.

In some parts of the country, wood is sold in "stovewood," "face," or "running" cords, "runs," or "ricks" composed of 12-, 16-, or 24-in. pieces in piles 4 ft high and 8 ft long. Three such piles of 16-in. wood actually contain somewhat more than one pile of 4-ft wood.

### General Characteristics of Wood

Contrary to popular conception, the terms hardwood and softwood have no reference to the actual hardness of the wood. According to the "Wood Handbook," prepared by the Forest Products Laboratory of the U.S. Department of Agriculture, hardwood refers to the botanical group of trees that are broad-leaved; softwoods, or conifers, refers to the botanical group of trees that have needle or scalelike leaves and are evergreen for the most part. Cypress, tamarack, and larch are exceptions.

The presence of considerable quantities of resins or oils, as in longleaf pine and eucalyptus, tends to raise the heating value of wood but causes it to be consumed faster. Pound for pound, resin gives almost twice as much heat as wood; it also produces more smoke.

Generally the softwoods (from cone-bearing trees) burn more readily than the hardwoods; and the lighter hardwoods are consumed faster than the heavier species. The pines, for example, make a quicker hotter fire and last a shorter time than birch, but birch gives a more intense flame than oak. Oak and hickory burn more slowly and give a steady heat.

American beech has long been a favorite fuel wood in the Northeastern and Central regions of the country, having heating value nearly equal to that of the best oaks. Eastern hop hornbeam or ironwood is also heavy and yields much heat per cord.

Chestnut, butternut, tamarack, and spruce have the objectionable property of throwing off sparks.

**Heat Value of Cordwood.** Moisture in wood is the most important factor in the heating value. Not only is the carbonaceous weight of the wood reduced by the amount of the water, but the water content must also be converted to superheated steam at the stack temperature. Generally from 25 to 45 per cent of the weight of green wood is water, and in such species as cottonwood and willow it may be even 55 or 60 per cent.

From 6 months to a year is usually required for thorough seasoning, with some woods benefiting by seasoning to a much greater extent than others, depending largely upon their initial moisture content.

The benefit through seasoning varies considerably with different species, depending upon such factors as the original moisture content. For example, *the following woods are improved comparatively little by drying*: ash (except black), beech, Douglas fir, Alpine fir, noble fir, pignut hickory, shagbark hickory, black locust, osage orange, red pine, lodgepole pine, red spruce, white spruce, tamarack (eastern larch).

On the other hand, *higher moisture content makes seasoning of the following woods more necessary*: red alder, black ash, paper birch, river birch, cottonwoods, grand fir, American elm, Pacific silver fir, white fir, hackberry, bitternut hickory, nutmeg hickory, honey locust, maples, oaks, pines (except red and lodgepole), red gum, sugarberry, sycamore, water tupelo, black walnut.

Some species, such as gray birch and aspen, give better results if not too dry, being consumed less rapidly.

**Table 5-7. Moisture Content of Cordwood under Various Conditions**

(Approximate only, as there is considerable variation at all levels)	
Green wood, as cut (except cottonwood and willow)	25-45 %
Green wood, as cut, cottonwood and willow	Up to 60 %
Seasoning 3 months, in reasonably dry weather <sup>a</sup>	About $\frac{1}{2}$ of full seasoning effect, and 90 % of fuel value
Seasoning 6 months to 1 year (depending on species)	Full seasoning effect
Fully seasoned, air-dried, commercial wood	15-20 %
<sup>a</sup> If the branches of live trees, felled during the summer, are left intact for 2 or 3 weeks, considerable moisture will be drawn out through the leaves.	

**Analyses of Cord Woods.** As is seen in Table 5-8 the analyses of uniformly dried woods of most common species are remarkably uniform. By ultimate analyses, carbon varies only from 48.8 to 55.0 per cent, hydrogen from 5.6 to 7.0 per cent, oxygen from 38.1 to 45.0 per cent, ash from 0.15 to 2.2 per cent, and high heat value from 8,400 to 9,870 Btu. Pitch pine is excepted in these figures, as its high resin content gives it a considerably higher heat content and somewhat different analysis.

*Typical proximate analysis of wood, on a dry basis, is as follows:*

	Per Cent
Volatile	81 5
Fixed carbon	17 5
Ash	1 0

**Table 5-8. Ultimate Analyses and Heating Values of Typical Dry Woods<sup>1</sup>**

	Ultimate analyses by weight, per cent						Heating value, Btu/lb		Air required for perfect combustion (zero excess air), lb/10,000 Btu	CO <sub>2</sub> at zero excess air, per cent
	C	H	S	O <sub>2</sub>	N <sub>2</sub>	Ash	Higher	Lower		
Softwoods: <sup>a</sup>										
Cedar, white.....	48 8	6 4	...	44 4	...	0 4	8,400 <sup>b</sup>	7,780	7 09	20 2
Cypress.....	55 0	6 5	...	38 1	...	0 4	9,870 <sup>b</sup>	9,234	7 12	19 5
Douglas fir.....	52 3	6 3	...	40 5	0 1	0 8	9,050	8,439	7 19	19 9
Western hemlock.....	50 4	5 8	0 1	41 4	0 1	2 2	8,620	8,056	7 05	20 4
Pine, pitch ... ..	59 0	7 2	...	32 7	...	1 1	11,320 <sup>b</sup>	10,620	7 02	18 7
Pine, yellow. ... .	52 6	7 0	...	40 1	...	1 3	9,610 <sup>b</sup>	8,927	7 09	19 2
Pine, white.....	52 6	6 1	...	41 2	...	0 1	8,900 <sup>b</sup>	8,308	7 22	20 2
Redwood.....	53 5	5 9	...	40 3	0 1	0 2	8,840	8,266	7 07	20 2
Hardwoods: <sup>a</sup>										
Ash, white .. .	49 7	6 9	...	43 0	...	0 3	8,920 <sup>b</sup>	8,246	7 09	19 5
Beech.....	51 6	6 3	...	41 4	...	0 7	8,760 <sup>b</sup>	8,151	7 28	20 1
Birch, white... .	49 8	6 5	...	43 4	...	0 3	8,650 <sup>b</sup>	8,019	7 14	20 0
Elm.....	50 4	6 6	...	42 3	...	0 7	8,810 <sup>b</sup>	8,171	7 17	19 8
Hickory.....	49 7	6 5	...	43 1	...	0 7	8,670 <sup>b</sup>	8,039	7 12	19 9
Maple.....	50 6	6 0	...	41 7	0 3	1 4	8,580	7,995	7 19	20 3
Oak, black....	48 8	6 1	...	45 0	...	0 15	8,180 <sup>b</sup>	7,587	7 13	20 5
Oak, red.....	49 5	6 6	...	43 7	...	0 15	8,690 <sup>b</sup>	8,037	7 11	19 9
Oak, white.....	50 4	6 6	...	42 7	...	0 2	8,810 <sup>b</sup>	8,169	7 13	19 8
Poplar.....	51 6	6 3	...	41 5	...	0 7	8,920 <sup>b</sup>	8,311	7 15	20 0
Avg.....	...	...	...	...	...	...	8,980			

<sup>1</sup> DE LORENZI, OTTO, "Combustion Engineering," pp. 25-27, Combustion Engineering Co., Inc., New York, 1947.

<sup>a</sup> As explained in the text, the terms softwoods and hardwoods refer to conifers and broad-leaved trees and not to the physical properties of the woods.

<sup>b</sup> Calculated from reported higher heating value of kiln-dried wood assumed to contain 8 per cent moisture.

**Table 5-9. Effect of Moisture Content on Heat Value of Wood and Wood Products**

Moisture, per cent	Heat value per lb, Btu	Heat required to evaporate water, Btu <sup>a</sup>	Net heat remaining, Btu	Lb water per lb dry wood
0	9,000	0	9,000	0 00
10	8,100	120	7,890	0 11
20	7,200	240	6,960	0 25
30	6,300	360	5,940	0 43
40	5,400	480	4,920	0 67
50	4,500	600	3,900	1 00
60	3,600	720	2,880	1,50
70	2,700	840	1,860	2 30
80	1,800	960	840	4.00
90	900	1,080	-180	9 00
100	0	1,200	-1,200	

<sup>a</sup> Assuming 500°F stack temperature.

**Table 5-10. Approximate Weight and Heating Value of Various Woods<sup>1</sup>**

Species	Weight per cord <sup>a</sup>		Available heat <sup>c</sup> per cord		Equivalent in coal <sup>d</sup>	
	Green, lb	Air-dry, <sup>b</sup> lb	Green, million Btu	Air-dry, <sup>b</sup> million Btu	Green, tons	Air-dry, <sup>b</sup> tons
Ash . . . . .	3,840	3,440	16 5	20 0	0 75	0 91
Aspen . . . . .	3,440	2,160	10 3	12 5	0 47	0 57
Beech, American . . . . .	4,320	3,760	17 3	21 8	0 79	0 99
Birch, yellow . . . . .	4,560	3,680	17 3	21 3	0 79	0 97
Elm, American . . . . .	4,320	2,960	14 3	17 2	0 65	0 78
Hickory, shagbark . . . . .	5,040	4,240	20 7	24 6	0 94	1 12
Maple, red . . . . .	4,000	3,200	15 0	18 6	0 68	0 85
Maple, sugar . . . . .	4,480	3,680	18 4	21 3	0 84	0 97
Oak, red . . . . .	5,120	3,680	17 9	21 3	0 81	0 97
Oak, white . . . . .	5,040	3,920	19 2	22 7	0 87	1 04
Pine, eastern white . . . . .	2,880	2,080	12 1	13 3	0 55	0 60

<sup>1</sup> Data from Forest Products Laboratory, as reported in "Wood Fuel in Wartime," *U.S. Dept. Agr. Farmers Bull.* 1912.

<sup>a</sup> Containing 80 cu ft of solid wood.

<sup>b</sup> Air-dry means with 20 per cent moisture in terms of oven-dry weight, or 16.7 per cent in terms of total oven-dry weight.

<sup>c</sup> Available heat equals calorific (Btu) value, minus loss due to moisture, minus loss due to water vapor formed, minus loss due to heat carried away in dry chimney gas. Flue temperature 450°F; no excess air.

<sup>d</sup> Heat value of coal under similar conditions taken as 11,000 Btu. This would require a good coal with a calorific value of about 14,000 Btu per lb of dry coal. Tons of 2,000 lb.

**Table 5-11. Woods Classified by the Number of Cords Required to Equal the Heat Value of 1 Net Ton of Anthracite<sup>1</sup>**

1 cord	1½ cords	2 cords
Hickory	Shortleaf pine	"Cedar"
Oak	Sweet gum (red gum)	Redwood
Beech	Douglas fir	Poplar
Sweet birch	Sycamore	Catalpa
Hard maple	Soft maple	Cypress
Rock elm	Slippery elm	Basswood
Locust	Black cherry	Spruce
Longleaf pine	Tamarack	White pine

<sup>1</sup> "Wood Fuel in Wartime," *U.S. Dept. Agr. Farmers Bull.* 1912. Based upon 80 cu ft of solid wood, seasoned to 15 to 20 per cent moisture by total weight.

Table 5-12. Cubic Feet of Solid Wood per Cord for Various Diameters of Sticks<sup>1</sup>

Diam of standing timber, breast high, in.	Chestnut		Black oak		White oak	
	Diam avg stick, in.	Cu ft/cord	Diam avg stick, in.	Cu ft/cord	Diam avg stick, in.	Cu ft/cord
2	1 8	63	1 8	63	1 8	63
3	2 6	70	2 5	69	2 5	69
4	3 3	75	3 1	74	3 1	74
5	4 0	79	3 6	77	3 5	76
6	4 7	83	4 1	80	3 9	79
7	5 2	85	4 5	82	4 2	81
8	5 8	88	4 8	84	4 5	82
9	6 2	89	5 0	85	4 7	83
10	6 7	91	5 3	86	4 9	84
11	7 0	92	5 4	86	5 0	85
12	7 4	93	5 6	87	5 1	85
13	7 7	94	5 7	88	5 2	85
14	7 9	94	5 7	88	5 2	85
15	8 2	95	5 8	88	5 3	86
16	8 4	95	5 9	88	5 4	86
17	8 5	95	5 9	88		
18	8 7	95	6 0	89		

<sup>1</sup> U.S. Dept. Agr. Forest Service Bull. 96.

### HOGGED FUEL<sup>1</sup>

The term "hogged fuel" is properly applied to wood slabs, bark, edgings, trimmings, etc., which have been put through a "hog" to reduce them to a uniform small size (usually from dust to about 5 cu in.), but the term is also loosely used for shavings from planing mills, sawdust from saw kerfs, bits of bark, chips, and other small products from the manufacture of lumber.

Several types of "hogs" are available, but virtually all operate on the essential principle of rapidly rotating knives or swing hammers in a suitable casing, which force the macerated and shredded wood through a perforated plate or series of spaced bars.

**Quantity Available.** In the manufacture of lumber, the total quantity of waste and by-products material will average about 50 per cent, of which 10 per cent is bark; 20 per cent slabs, edging, and trimming; and 20 per cent shavings and sawdust. (This distribution may vary widely in specific mills because of local conditions and type of finished product.) Sawdust and some shavings can usually be burned without further processing; but larger material is usually "hogged" to facilitate handling and combustion. In typical Northwestern sawmills the salable surplus of hogged fuel, above the mill requirements, usually averages about 100 lb per 1,000 ft of logs handled.

Hogged fuel is sold by the "unit," a unit consisting of 200 cu ft as measured without tamping or packing. The weight of a unit will vary from 1,700 to 2,300 lb of dry wood (up to 5,000 lb, as received) depending on the species, moisture, and fine-material content.

Like wood, the principal characteristics of hogged fuel are high moisture, high volatile, low carbon, and high oxygen. The moisture must be evaporated before combustion can take place; the volatile matter, amounting to about 80 per cent of the dry fuel, must be burned above the grate; and the fixed carbon, about 20 per cent of the dry fuel by weight, burned on the grate. As is the case with all wet fuels, the dried fuel and the distilled gases should be burned in close proximity to the incoming wet wood, to ensure more rapid evaporation.

<sup>1</sup> DE LORENZI, OTTO, "Combustion Engineering," Combustion Engineering Co., Inc., New York 1947. "Finding and Stopping Waste in Modern Boiler Rooms," Cochrane Corp., Philadelphia, 1928.

Hogged fuel stored outdoors shrinks 10 to 25 per cent from settling after rains and, according to Cochrane, also loses about the same amount in heating value from escaping volatiles. Little further depreciation occurs after 6 months.

Table 5-13. Analyses of Hogged Fuels<sup>1</sup>

	California redwood	Western hemlock	Douglas fir	Pine sawdust
Moisture as received, per cent	50.4	57.9	35.9	
Moisture air-dried, per cent	7.3	7.3	6.5	6.3
Proximate analysis, dry fuel:				
Volatile matter, per cent....	82.5	74.2	82.0	79.4
Fixed carbon, per cent ....	17.3	23.6	17.2	20.1
Ash, per cent. ....	0.2	2.2	0.8	0.5
Ultimate analysis, dry fuel:				
Hydrogen, per cent. ....	5.9	5.8	6.3	6.3
Carbon, per cent. ....	53.5	50.4	52.3	51.8
Nitrogen, per cent. ....	0.1	0.1	0.1	0.1
Oxygen, per cent. ....	40.3	41.4	40.5	41.3
Sulphur, per cent. ....	0	0.1	0	0
Ash, per cent. ....	0.2	2.2	0.8	0.5
Btu per lb (dry) ..	9,920	8,620	9,050	9,130

<sup>1</sup> U.S. Bureau of Mines.

## INDUSTRIAL USE OF WOOD WASTE

In contrast with the earlier days of lumbering, when all bark, chips, sawdust, and other small material that could not be burned as a fuel was wasted, there is now a profitable market for all such by-products. As a result, many new sawmills, particularly the larger ones, are being built without any waste burners. In frequent instances, even the boiler plant can no longer depend upon hogged fuel as a power source.

An example of this modern concept is the Longview, Wash., plant of the Weyerhaeuser Timber Co.<sup>1</sup> Here are located on one site three sawmills, a planing mill, plywood plant, sulphite-pulp mill, sulphate-pulp mill, bark-products plant, and a Pres-to-log plant. All are interconnected by suitable mechanical handling and conveyor systems.

In the plywood plant a specially designed **pneumatic barker** cleanly separates the thick Douglas-fir bark by means of tearing jets of water at approximately 1,500 psi.

**Douglas-fir bark**, after being ground and screened, is used for a wide variety of products, ranging from insecticide powders to soil conditioners and plastic molding compounds.

In the **sulphite-pulping plant**, hemlock and white fir logs, together with chunks and partly defective material, are converted to pulp. Logging leftovers from prelogging and relogging contribute a substantial part of the raw materials for this plant.

The **sulphate mill** obtains most of its Douglas-fir supply from slabs, trimmings, edgings, and other leftovers from the sawmills supplemented by thinnings from second-growth forests.

The **Pres-to-log plant** compresses planing-mill shavings and other dry leftovers into a domestic fuel for fireplaces.

The **full use of the bark** from these woods results in savings of some 17 volume per cent of which about 12 per cent is in the form of the bark and the additional 5 per cent is, as a result of the hydraulic debarkers, clean separation of bark without waste of wood.

<sup>1</sup> "Oil-power," pp. 8 and 9, Socony-Vacuum Oil Co., July and August, 1948.



## PEAT, WOOD, CHARCOAL, AND AGRICULTURAL WASTES

Table 5-14. Characteristics of Sawmill-refuse Fuels<sup>1</sup>

Wood	Usual location	Moisture per cent	Fuel characteristics
Birch	Mich.	40-45	Fair
Cedar	W. Wash., Ore., B.C.	45-55	Fair
Cedar	Central Calif.	40-50	Fair
Cypress	Fla., Tex., Miss.	35-54	Fair
Fir	Wash., Ore., B.C.	35-45	Good
Fir	Central Calif.	35-50	Poor
Hemlock	Wash., Ore., B.C.	40-50	Poor
Hemlock	Mich.	45-55	Poor
Maple	Mich.	45-55	Fair
Pine cork	E. Wash., Idaho	35-45	Fair
Pine, longleaf	Fla., Gulf Coast	40-50	Fair
Pine, shortleaf	Fla., Gulf Coast	20-40	Fair
Pine, shortleaf	Fla., Gulf Coast	40-50	Fair
Pine, white	Mexico	35-55	Fair
Pine, sugar	Calif.	40-55	Poor
Pine, yellow.	Calif. (central)	40-45	Fair
Redwood	Calif.	45-50	Poor
Pine, white	Calif.	35-45	Fair

<sup>1</sup> CORBET, DARRAH, from "Cochrane Handbook," Philadelphia, 1928.

WOOD BARK<sup>1</sup>

Despite modern methods for converting much of the formerly wasted materials from lumber and pulp mills into marketable products, large quantities of bark and wood chips continue to serve as a fuel, particularly in the smaller mills.

**Quantity Available.** Studies made by various Pacific Northwest operators indicate that from 1,320 to 2,130 lb of wet bark, or 475 to 740 lb on a dry basis, per ton of unbleached pulp are produced when hemlock and white-fir logs are used. This wide variation is due to many factors, among which are the type of debarking method used, the size of the logs being handled, the time of the year in which the logs are cut, and the method of handling from the forest to the barking equipment.

While in some smaller, less well-equipped plants bark and waste may be so plentiful as to constitute a disposal problem, especially in the summer when lumbering is at its peak and heat is not needed, the general practices are such, particularly in the larger plants, that bark and waste production are reduced to only a small fraction of the total fuel requirements, the remainder being supplied by conventional oil- or coal-fired equipment.

Surprisingly, for the same species of wood, as much as 75 per cent more bark will be obtained from logs cut in the fall and winter than from those cut in the spring when the sap has started to flow and the bark is readily scabbed off.

**Moisture and Drying.** The moisture content of bark also depends upon several factors. A conventional method of debarking tumbles the logs in huge revolving open-ended cylinders without adding moisture in the process; a newer method employs hydraulic jets which, as the name implies, add considerable moisture. The logs may be hauled dry or floated to the mill, may be used as received, or may undergo a drying period before use.

According to Freiday, the moisture content of bark, as received, ranges from 60 to 80 per cent for Northern mills and 45 to 55 per cent for Southern mills. He attributes

<sup>1</sup> FREIDAY, J. H., *Bark Burning Methods, Combustion*, October, 1947, pp. 45-46. "Wood Fuel in Wartime," *U.S. Dept. Agr. Farmers Bull.* 1912, 1942. HARRIS, D. W., *The Combined Firing of Coal and Wood Refuse, Paper Mill News*, Mar. 5, 1949, pp. 10-13.



other trees, such as the "cedars," or junipers, has a low heat value and produces much smoke.

Formerly it was often considered more economical to dump, rather than to burn, bark. Today, with rising fuel and labor costs, the disposal of bark of even 70 per cent moisture should be considered as a means for economical production of steam rather than an incinerator problem.

**Ash Content.** While the inherent ash content of bark is low (Table 5-15, 0.5 to 5.0 per cent), the practice of dragging and floating the logs, particularly in northern forests, accumulates much mud and silt to add materially to the difficulties of burning.

One of the major points to be considered in designing a furnace for the combined burning of coal and wood refuse is the effect of the fluxing action of the wood ash. The impurities in the ash, particularly if the logs have been stored in salt water, are likely to reduce the coal-fusion temperature to aggravate clinker and slagging difficulties. Where normal softening temperatures of the coal ash are low, this point can be critical. Table 5-15 includes analysis of various wood-bark ashes as compiled by Babcock & Wilcox Co.

**Handling.** Handling of wood bark is complicated when the bark is peeled from the logs in long ropelike strips. These should be cut up, or "hogged," for proper combustion.

Table 5-15. Typical Analyses of Wood Bark<sup>1</sup>

	Douglas fir	Cedar	Lodge- pole pine	White fir	Hem- lock	Spruce	Red- wood
Salt-water storage . . . . .	No	No	No	Yes	Yes	Yes	Yes
Proximate analysis:							
Volatile matter, per cent . . . . .	72.9	73.0	73.5	74.3	72.5	69.6	72.6
Fixed carbon, per cent . . . . .	25.9	21.9	26.0	24.0	25.8	26.6	27.0
Ash, per cent . . . . .	1.3	5.1	0.5	1.7	1.7	3.8	0.5
Sulphur, per cent . . . . .	Trace	Trace	Trace	Trace	0.03	0.1	Trace
Btu per lb (dry) . . . . .	9,570	8,610	9,310	8,810	9,090	8,740	8,350
Ultimate analysis:							
Carbon, per cent . . . . .	56.2	51.0	55.0	52.2	53.7	51.8	51.9
Hydrogen, per cent . . . . .	5.9	5.7	5.8	5.8	5.7	5.7	5.1
O <sub>2</sub> and N <sub>2</sub> (difference) . . . . .	36.7	38.2	38.7	40.3	38.9	38.6	42.6
Ash analysis:							
Silica, SiO <sub>2</sub> . . . . .	13.9	44.0	12.2	1.7	1.5	32.0	14.3
Iron as Fe <sub>2</sub> O <sub>3</sub> . . . . .	4.4	7.2	5.6	3.2	3.6	6.4	3.5
Titanium oxide, TiO <sub>2</sub> . . . . .	0.4	0.8	0.3	0.0	0.0	0.8	0.3
Alumina, Al <sub>2</sub> O <sub>3</sub> . . . . .	8.7	13.8	8.7	3.2	1.7	11.0	4.0
Manganese, Mn <sub>2</sub> O <sub>4</sub> . . . . .	0.3	0.1	0.2	3.9	3.3	1.5	0.1
Calcium oxide, CaO . . . . .	51.4	13.9	48.0	60.8	58.2	25.3	6.0
Magnesium oxide, MgO . . . . .	3.2	3.1	1.8	3.0	4.4	4.1	6.6
Sodium oxide, Na <sub>2</sub> O . . . . .	5.3	6.6	8.4	10.4	9.1	10.4	25.0
Sulphate as SO <sub>3</sub> . . . . .	2.9	3.1	3.3	3.0	3.7	2.1	7.4
Chloride, Cl . . . . .	0.4	0.7	0.4	0.4	1.4	Trace	18.4
Carbonate, as CO <sub>2</sub> . . . . .	7.3	5.2	9.1	11.5	11.8	7.0	14.0
Unaccounted for . . . . .	1.8	1.5	2.0	1.1	1.3	0.6	0.4

<sup>1</sup> Compiled by Babcock & Wilcox Co., research and development department.

## BURNING WOOD BARK AND REFUSE IN COMBINATION WITH COAL AND SEPARATELY<sup>1</sup>

A number of different means for burning wood bark in combination with coal have been employed with varying degrees of success.

<sup>1</sup> Abstracted from HARRIS, D. W., The Combination Firing of Coal and Wood Refuse, *Paper Mill News*, May 5, 1949, pp. 10-13.

**Hand-firing.** Premixed coal and hogged-wood fuel is frequently gravity-fed to grates through the roof of a Dutch oven in front of the boiler. Labor for mixing and firing the fuel and for cleaning the fires at least every 8 hr constitutes the principal disadvantage.

**Underfeed Stokers.** Another early method consisted in dropping the wood refuse on an underfeed-stoker fuel bed (coal) through chutes in the front wall of the furnace. Water-cooled stoker retorts are desirable to hold maintenance within reasonable limits.

**Pulverized-coal Furnaces.** A Hofft water-cooled step-grate type of furnace was located in a separate Dutch oven in front of a pulverized-coal-fired boiler, for the combination firing of pulverized coal and wood waste. Arrangements minimized the carry-over of wood ash to the boiler furnace. On the other pulverized installations, small quantities of wood have been burned merely by dropping them through the roof of the pulverized-coal furnace and admitting air through pinhole grates in the furnace floor.

**Spreader Stokers.** The use of spreader stokers was tried in England at least 50 years ago. Modern units with stationary, dumping, and traveling grates have all been extensively tried with wood-coal fuels. The wood has been fed both through the rotor with the coal and into the fuel stream from a chute located above the rotor; the latter is now preferred.

Considerable success has been achieved with the spreader stoker on wood-coal fuels, but certain problems of feeding and burning dictate most careful attention to design details. Included are the tendency of the light bark to pile up at the forward end of the grate; the necessity for auxiliary air as an aid to satisfactory fuel distribution; and the aggravation of any tendency for the coal to clinker because of the fluxing effect of the wood ash.

### Burning Wood Bark Separately

Burned without admixture with coal, wood bark is usually either fed through the roof of Dutch ovens where it burns in conical piles on flat grates or fed through openings of the front walls of Dutch ovens equipped with inclined grates, the fuel moving to the back of the grate as combustion progresses. The fuel bed is obviously more uniform in thickness when the inclined grate is used.

### Some Recent Developments in the Burning of Wet Wood<sup>1</sup>

The most widely available refuse fuel is some form of wet wood. In this discussion, wood containing above 30 per cent moisture, on the as-received basis, is considered as "wet."

Wet wood is a large-quantity by-product to the manufacture of lumber, pulp, and the so-called "naval stores" such as pine pitch and resin. When used for steam generation, it falls into three broad classifications, each of which has its own combustion problems:

1. Sawmills in which much of this fuel is produced. Included are shavings, bark, sawdust, and other wood waste in various proportions. "Hogged fuel," usually composed of chips with little or no sawdust and shavings, also falls into this class.

2. Wet-wood refuse produced in the wood-preparation plants of pulp and paper mills is in the second class. Here the principal problem is the disposal of wet bark.

3. Pine pitch, resin, and other products obtained from pine stumps which have been chipped, mixed with a solvent and steam-cooked in so-called "naval stores" plants constitute the third class. These plants are concentrated in the Southeastern part

<sup>1</sup> DE LORENZI, OTTO, Director of Education, Combustion Engineering-Superheater, Inc., *Mech. Eng.*, September, 1949, pp. 735-738.

of the United States. The "spent" wood chips, minus the recovered pitch and resin, are available for steam production.

### Burning Lumber-mill Refuse

**Dutch-oven Furnaces.** For lumber-mill installations the furnace most frequently used is of the two-stage type comprising a Dutch oven for drying and gasification and a secondary chamber in which the combustion of the gaseous products is completed. Inasmuch as wet-wood burning is largely a matter of surface combustion, the use of refractory arches and walls in the primary, or Dutch-oven, furnace is of considerable importance. Their function is to provide the maximum possible amount of radiant and reflected heat for maintaining gasification and preventing the fire from becoming extinguished, even though the overfeeding principle of continually supplying fresh fuel to the surface of the ignited cone-shaped pile is used.

Dutch-oven installations are quite successful but have such disadvantages as frequent service interruptions such as for slag removal and refractory or grate renewals, and the necessity for continuous changes in regulation because of the largely non-controllable air and fuel supplies.

**Underfeed Method of Burning.** De Lorenzi<sup>1</sup> describes an experimental underfeed-burning method, designed to overcome these objections. Wood is supplied to an underfeed retort by a reciprocating ram. The fuel is burned in a pile but, instead of being continually showered from above, is gradually forced upward through the pile. Automatic regulation can be applied. Some of de Lorenzi's<sup>1</sup> data from this experimental installation are shown as Table 5-16.

The objective is a single-stage furnace, with high combustion rates and efficient compact design.

Table 5-16. Results with Underfeed Firing of Wet Wood<sup>1</sup>

	Moisture, per cent	CO <sub>2</sub> , per cent	Lb/hr	Lb/ sq ft/hr
Southern pine....	51 4	17 5	7,500	117
Southern pine . . .	51 4	17 0	12,750	200
Spent pine chips.. . .	66 5	16 0	13,150	206
California redwood . . . .	54 0	16 9	11,200	175
California redwood . . . .	50 9	15 7	10,930	170
California redwood . . . .	57 8	18 8	15,300	240
California redwood . . . .	49 1	17 3	14,550	227
California redwood . . . .	57 8	15 6	7,880	123

<sup>1</sup> DE LORENZI, OTTO, Some Recent Developments in Burning Wet Wood, *Mech. Eng.*, September, 1949, pp. 735-738.

### Burning Wet Bark<sup>1</sup>

De Lorenzi describes the two-stage Dutch-oven furnace as the best known way of burning excessively wet bark. Supplementary fuels are usually necessary to bridge gaps in the inconstant bark supply.

One large Middle Western paper mill has installed generating units designed for wet-wood refuse and pulverized coal. The wood is burned in the Dutch oven, the coal in the secondary combustion chamber.

In many Southern mills the sloping-grate furnace has been used for wet bark. Air supply is sectionalized to provide drying and burning zones. Supplementary oil fuel is sometimes used where the supply of wood is not continuously adequate.

<sup>1</sup> DE LORENZI, OTTO, *Mech. Eng.*, September, 1949, pp. 735-738.

Newer installations have used spreader stokers with marked success. In these, improved sizing of the wood before use is usually necessary. High capacity, instant response to changes in steam demand, and adaptability to automatic control characterize such units. Continuous combustion rates of 155 lb of wet wood or 700,000 Btu/hr/sq ft of grate are reported by de Lorenzi (45 per cent moisture content wood). The single-stage furnace is usually water-cooled and the spreader unit, while located somewhat higher above the grate than for straight coal firing, is nevertheless well below the point at which products of combustion enter the boiler bank. Coal may be used as an auxiliary fuel.

### Burning Spent-wood Refuse from Naval Stores<sup>1</sup>

Spent-wood refuse from naval-stores plants has characteristics that are considerably different from woods just described. Spent-wood chips, having had the resin and pitch removed, are devoid of the flashy burning characteristics of pine.

The accepted furnace design is of the sloping-grate type, having relatively low capacity and requiring considerable manual labor for sand and char removal. Normal continuous capacity for furnace widths of 10 ft is from 30,000 to 40,000 lb of steam per hr with CO<sub>2</sub> of 10 to 12 per cent and volumes of black smoke continuously rolling from the stack. Response to changes in steam demand is extremely sluggish.

De Lorenzi describes an experimental furnace designed to overcome such difficulties. A combination of special spreader-fuel feed; tangential jets in four alternate belts; a traveling grate; and a tall single-stage water-cooled furnace has been in very successful operation for over 2 years.

The unit is described as operating continuously at a capacity of 100,000 to 120,000 lb of steam per hr and a CO<sub>2</sub> of from 16 to 18 per cent with smoke of approximately No. 1 Ringelman density. This is obviously a material improvement over previous designs.

### TANBARK

Tanbark is the fibrous portion of ground oak or hemlock bark used in tanning. Spent tan, as rejected by the tannery and available as a fuel, normally contains about 65 per cent moisture. The dry-basis analysis is about as follows:

Carbon, per cent .....	51 80
Hydrogen, per cent. ....	6 04
Oxygen, per cent. ....	40 74
Ash, per cent....	1 42
Btu (dry). . . . .	9,500

As is the case with other wood barks, partial drying before use can be accomplished by pressing or by waste-heat drying. Methods of burning, effect of moisture on reducing heat value, and other characteristics and procedures are as discussed for wood and barks elsewhere in this chapter.

### RESIDUE FROM TURPENTINE-EXTRACTION PROCESS<sup>2</sup>

This fuel consists of yellow pine chips from which the resinous substance has been extracted. According to de Lorenzi, the pieces are uniformly sized, and are 1 to 1½ in. long, by ⅓ to ¼ in. thick. The fuel as burned contains about 35 per cent moisture. The following is a typical proximate analysis by weight on a dry basis:

Volatile matter, per cent .....	83 5
Fixed carbon, per cent....	14 5
Ash, per cent.....	1.1
Btu.....	9,180

<sup>1</sup> *Ibid.*

<sup>2</sup> DE LORENZI, OTTO, "Combustion Engineering," pp. 2-48, Combustion Engineering Co., Inc., New York, 1947.

A corresponding ultimate analysis shows 52.3 per cent carbon, 6.25 per cent hydrogen, 40.3 per cent oxygen plus nitrogen, 0.02 per cent sulphur.

"Combustion Engineering" states that the fuel is burned in a Dutch-oven-type furnace on an inclined grate.

### CHARCOAL

When carbonaceous materials are burned in a closed retort with insufficient air, the volatile is driven off and a residue of coke or charcoal is left. The term coke is usually reserved for residues from coal and petroleum products, while those from a wide variety of woody, agricultural, and animal products are known as charcoal. Such sources commonly include wood, coconut shells, bone, leather, rice hulls, etc. Charcoal intended for fuel and blast-furnace use is made from cordwood by low-temperature distillation in by-product retorts, in brick kilns, and formerly in heaps covered with earth called "meilers."

Charcoal differs widely according to its source; in fact, the source can be readily identified under a microscope. Of the wood charcoals, that made from willow is the softest, and that made from oak is hard and close-grained. For blast-furnace use, hardwoods, such as maple and birch, make the best charcoal, although those from softer woods can be used. For gas masks, coconut-shell charcoal is by far the best, having an absorptive index  $1\frac{1}{2}$  times that of the runner-up, logwood. The specific gravity of charcoal ranges from 1.3 to 1.9.

**Blast-furnace Use.** From every angle, except cost and availability, charcoal is the ideal fuel for blast-furnace use. Its low combined carbon and high volatile make its reactivity greatest of all blast-furnace fuels. It produces the highest quality pig but requires the greatest amount of labor. It is the only fuel which can perpetuate itself (reforestation every 15 to 20 years). The best blast-furnace charcoal is made when the trees are cut before the sap comes up and then stacked to dry.

As a result of its adaptability, charcoal was the only blast-furnace fuel used in the United States until 1840. As late as 1905, the Algoma Steel Co., Sault Sainte Marie, Ontario, the largest charcoal blast furnace in the world, used a charcoal pile  $\frac{1}{2}$  mile long every 24 hr.

Sweetser<sup>1</sup> lists the following advantages of charcoal over coke:

1. The furnace consumes considerably less charcoal than coke per ton of pig iron.
2. Only one-third as much limestone per ton of pig iron is required in a charcoal furnace.
3. The amount of blast required for a charcoal furnace is only about 65 per cent of that for a coke furnace of the same productive capacity.
4. The "critical temperature" in a charcoal furnace may be lower than in a coke furnace.

As against such important advantages, the only disadvantages listed by Sweetser are the difficulty of obtaining a sufficient supply (a cordwood pile 1 mile long is required to make charcoal for 150 tons of pig iron), and the readiness with which charcoal catches fire (even in the upper part of the furnace, there is danger of trouble if the furnace makes a heavy slip when using dirty charcoal).

**Charcoal as a Fuel.** Charcoal has an average heating value of about 11,000 Btu. It ignites and burns easily and without smoke. It is thus an ideal fuel for certain uses such as small forges, grills, for starting small furnace fires, etc., particularly in instances where the nature of the use limits the draft to a minimum. It is used somewhat extensively in certain types of tobacco curing, as in Connecticut, where it is burned openly in small pits or pans for the few hours needed to start the curing process.

<sup>1</sup> SWEETSER, RALPH H., Charcoal and Coke as Blast Furnace Fuels, *Trans. ASME*, vol. 39, 1909.

The principal disadvantage even for such specialized use is the very high present-day cost of charcoal.

**Charcoal for Other Uses.** The original surface area of charcoal is enormous. It has been estimated by Lagergen that 1 g of charcoal has a surface of 4 sq miles and is composed of 1.4 billion particles; Lamb, Wilson, and Chaney estimate that 1 cc of active gas-mask charcoal has a surface of 1,000 sq miles at its most effective density of 0.4. This gives rise to a wide and important field of uses utilizing the absorptive and adsorptive properties of charcoal. Among these a few of the more important are as the active agent in gas masks; in a wide field of deodorizing; in removing color from liquids, as in the refining of sugar; in removing the rarer metals from their solutions; in eliminating tastes and odors from water; and as a pharmaceutical for absorbing unwanted or harmful alkaloids, toxins, poisons, and certain bacteria.

**Activation of Charcoal.** The ability of natural charcoal to adsorb is greatly augmented by one of several processes of "activation." These usually consist of some method of depositing carbon on a porous inorganic base such as pumice, and are accompanied by various trade names.

**Table 5-17. Typical Actual Analyses of Charcoals<sup>1</sup>**  
(In per cent)

Source	Moisture	Volatile	Fixed carbon	Ash	Sulphur	Phosphorus
Maple, body wood . . . . .	0 27	24 27	71 53	3.93	0.037	0.020
Maple, small limbs . . . . .	0 14	29 80	63 95	6.11	0 031	0.030
Maple, body wood, bottom of ear	0 82	23 89	74 02	1.27	0 034	0 011
Elm, body wood . . . . .	0 73	23 28	75 84	1 15	0 030	0.018
Birch, body wood, bottom of ear	0 98	22 01	77 04	0 97	0 045	0 009
Maple, bark . . . . .	1 00	25 59	62.49	10.92	0 160	0.056
Ironwood . . . . .	0 58	27 50	70 33	1 59	0.027	0.015
Fine charcoal dust....	20 35	13 69	54 77	11 19	.....	0.078

<sup>1</sup> SWEETSER, RALPH H., "Blast Furnace Practice," p. 116, McGraw-Hill Book Company, Inc., New York, 1938.

**ASH ANALYSIS.** A typical ash analysis, taken from a 2.9 per cent ash charcoal, is silica, 0.55 per cent; alumina plus ferric oxide, 0.60 per cent, calcium oxide, 1.15 per cent; magnesium oxide, 0.50 per cent; alkalies, 0.07 per cent; and phosphorus, 0.03 per cent. (Note that these figures are based on per cent of the original charcoal and not per cent of ash content).

## AGRICULTURAL PRODUCTS AND AGRICULTURAL WASTES

Agricultural products, particularly those of low-grade and by-product otherwise waste materials, represent a tremendous potential source of fuel supply. This may assume one of three forms: (1) burning the product direct, as with woods, wood wastes, straw, corncobs, and bagasse; (2) fermenting the liquor and recovering alcohol, as with blackstrap molasses, potatoes, corn, and various vegetables and fruits, particularly surpluses and culls; and (3) recovering all possible alcohol from the fermented liquor and then burning the spent refuse, as with sugar cane and sulphite pulp.

Difficulties encountered in the really widespread use of such materials usually are not technical, since both the extraction and combustion of most such products are well understood, but lie in their collection from some 7 million farms scattered over the country, in the location of a large percentage of the products at points where there is little need for any great production of heat or power, in rapid geographical shifts in the concentration of available materials as the maturing of crops follows the climate, and in the highly seasonal nature of production, which is usually greatest when the need for heat and power is least.



Table 5-18 shows the estimated quantities of the principal cellulose farm waste products in the United States and the probable quantities that would be available to industry.

**Table 5-18. Principal Farm Wastes Produced and Available to Industry<sup>1</sup>**

Material	Principal sources	Total production, tons	Probable tons available to industry per year
Bagasse . . . . .	Fla., La., and U.S. insular possessions	3,801,425	2,740,000
Corncobs . . . . .	Iowa, Ill., Ind., Mo., Neb., Ohio	17,426,000	5,275,000
Cornstalks . . . . .	Iowa, Ill., Ind., Mo., Neb., Ohio	104,000,000	64,166,000
Cotton, bolls and stalks . . . .	Ala., Ark., Ga., La., Miss., N.C., Okla., S.C., Tex.	20,450,000	14,314,000
Hulls:			
Oat . . . . .	Ill., Iowa, Minn., Wis.	5,280,000	321,475
Rice . . . . .	Ark., Calif., La., Tex.	195,000	189,282
Seeds:			
Grape . . . . .	Calif.	79,258	31,780
Raisin . . . . .	Calif.	32,800	24,500
Shells and pits:			
Peanut shells . . . . .	Ala., Ga., N.C., Va., Tex.	240,000	75,000
Peach pits . . . . .	Calif., Ga.	190,750	46,200
Apricot pits . . . . .	Calif.	22,580	19,200
Straws:			
Barley . . . . .	Iowa, Minn., Neb., N.D., S.D., Wis.	6,901,000	5,176,000
Flaxseed . . . . .	Minn., Mont., N.D., S.D.	1,671,000	1,367,000
Oat . . . . .	Ill., Iowa, Minn., Wis.	22,883,000	1,149,000
Rice . . . . .	Ark., Calif., La., Tex.	1,169,000	877,000
Rye . . . . .	Minn., N.D., S.D.	2,797,300	2,098,300
Wheat . . . . .	Kans., Minn., N.D., S.D.	49,954,000	37,465,000

<sup>1</sup> Motor Fuels from Farm Products, *U.S. Dept. Agr. Misc. Pub.* 327, p. 110, 1938.

## BAGASSE

Bagasse is the refuse from the grinding or extraction of sugar from cane. It represents about 20 per cent of the weight of the original cane and is widely used as a fuel in sugar mills where large amounts of steam are required for power and to concentrate the raw sugar juice.

Bagasse has a fibrous structure and analysis similar to that of wood. Its appearance is similar to that of excelsior. The ash content may vary considerably in proportion to the amount of soil and other foreign matter picked up during the harvesting of the cane. Although the normal ash content is not high (1½ to 3 per cent), slagging difficulties are frequently encountered because of the high fusibility of the silt component.

The normal composition is about 35 to 45 per cent fiber, 7 to 10 per cent sucrose and other combustible material, and from 45 to 55 per cent moisture. Dry bagasse analyzes about 45 per cent carbon, 6 per cent hydrogen, 46 per cent oxygen, and from 1½ to 3 per cent ash.

**Heat Value of Bagasse.** While dry bagasse will average from 8,000 to 9,000 Btu per lb, the moisture content of the raw material reduces the heat actually for steam generation to about half of this amount (see Table 5-19). Fortunately, this is seldom a problem, since the average sugar mill has more bagasse than is needed, and lowered efficiency is thus welcome as a means for disposing of otherwise troublesome waste.

However, in poorly balanced mills, mills that refine their own sugar or distill alcohol or generate power in excess of that required in the mill, efficiency does become a

problem; in some cases of this sort, supplementary fuels, such as oil or gas, are burned in combination with the bagasse.

**Drying.** With the exception of early practices, when bagasse was spread in fields to sun-dry in order to burn it in ways which would not have accommodated wet bagasse, the general conclusion has been that the most economical way to dry bagasse is in the furnace. Gilg<sup>1</sup> points out that this may be changed to take advantage of the efficiency, simplicity, and flexibility of burning pulverized predried bagasse and oil in more conventional equipment. If so, he suggests water-cooled furnaces and circular turbulent burners using a minimum of excess air.

**High rates of combustion** characterize the burning of bagasse. Four tests reported by Gilg<sup>1</sup> were at rates of from 291 to 437 lb of bagasse per sq ft of grate per hr at efficiencies averaging 62.4 per cent. (According to "Combustion Engineering," the most economical rate is 200 to 225 lb of dry bagasse per hr.)

In brief, it is best burned in a pile and in large quantities. Ample high-temperature refractory surfaces are needed for prompt ignition. Combustion methods are similar to those for hogged fuel, in Dutch-oven-type furnaces on inclined grates, or in horse-shoe-shaped hearths. Fuel is fed through an opening in the roof of the furnace and burned in conical piles.

Table 5-19. Fuel Value of Green Bagasse<sup>1</sup>

Per cent of extraction of weight of cane	Moisture in bagasse, per cent		Btu/lb available for steam generation		Lb of bagasse equivalent to 1 lb of 14,000-Btu coal	
	a	b	a	b	a	b
75	42 64	51 00	4,139	3,294	3 38	4 25
77	39 22	48 07	4,475	3,630	3 13	3 86
79	35 15	44 52	4,874	3,976	2 87	2 52
81	30 21	40 18	5,359	4,392	2 61	3 19
83	24 12	35 00	5,958	5,005	2 35	2 80
85	16 20	28 33	6,716	5,558	2 08	2 52

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 803, McGraw-Hill Book Company, Inc., New York, 1941.

<sup>a</sup> Based upon tropical cane of 12 per cent fiber and juice containing 18 per cent of solid matter.

<sup>b</sup> Based upon Louisiana cane of 10 per cent fiber and juice containing 15 per cent of volatile matter.

Table 5-20. Typical Analyses of Dry Bagasse<sup>1</sup>

Country of origin	Ultimate analyses by weight, per cent					Heat value, Btu/lb		Air required (no excess air) lb/10,000 Btu	CO <sub>2</sub> at zero excess air, per cent
	C	H	O <sub>2</sub>	N <sub>2</sub>	Ash	Higher	Lower		
Cuba .....	43 2	6 0	47 9	....	2 9	7,985	7,402	6 25	21.0
Hawaii .....	46 2	6 4	45 9	....	1 5	8,160	7,538	6 87	20.3
Java .....	46 0	6 6	45 6	0.18	1 7	8,861	8,043	6.51	20.1
Mexico .....	47 3	6 1	35 3	....	11 3	9,140	8,548	6.67	19.4
Peru .....	49 0	5 9	43 4	..	1 7	8,380	7,807	6.99	20 5
Puerto Rico .....	44.2	6 3	47.7	0 41	1 4	8,386	7,773	6 25	20.5

<sup>1</sup> DE LORENZI, OTTO, "Combustion Engineering," pp. 25-27, Combustion Engineering Co., Inc., New York, 1943.

<sup>1</sup> GILG, F. X., Utilizing Bagasse as Fuel, *ASME Tech. Paper* 48-S-3, spring meeting, New Orleans, March, 1948.

"Combustion Engineering" gives the following formula for computing the Btu per pound of bagasse from its analysis:

$$H_f = 8,550 (FR) + 7,119 (SS) + 6,750 (GS) - 972 (H_2O)$$

where *FR* (fiber), *SS* (sucrose), *GS* (glucose), and  $H_2O$  (moisture) are all in pounds per pound of fuel as fired.

**Combustion of Bagasse.**<sup>1</sup> Despite its high moisture content,<sup>2</sup> bagasse burns very easily on the surface of an incandescent pile in specially designed furnaces containing sufficient hot brickwork to drive off the moisture and having the correct facilities for introducing combustion air in proper quantities and direction. Like most other solid fuels, the more finely the bagasse is divided, the easier it is to burn.

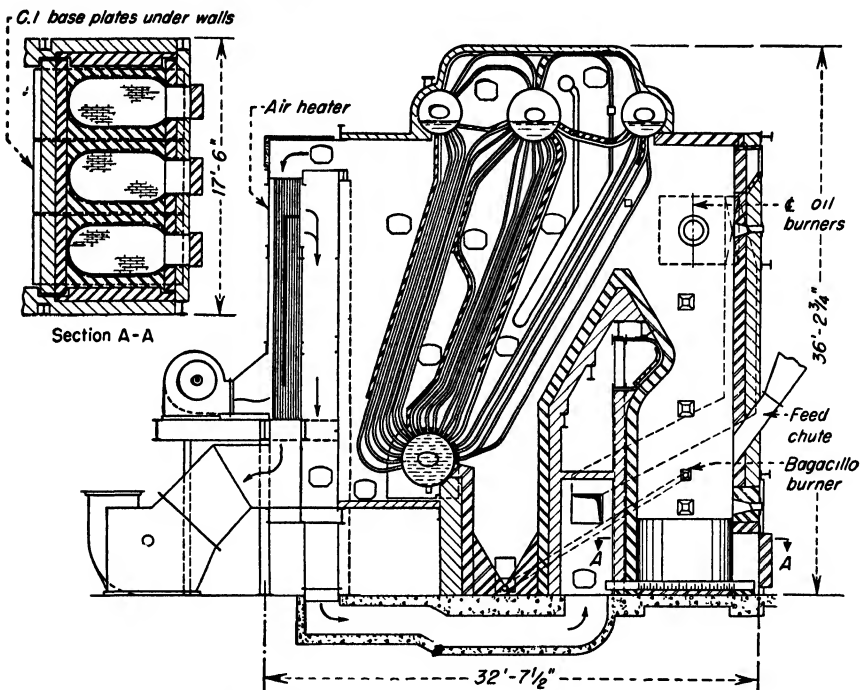


FIG. 5-2. General design of Ward furnace applied to modern Stirling boiler for burning bagasse. (F. X. Gilg, ASME Paper 48-S3, 1948.)

**Early Furnace Designs.** After the discovery that green bagasse would burn satisfactorily in a Dutch-oven type of furnace with natural-draft grates, numerous types and shapes of grates and furnaces were designed. The most successful types burned the bagasse on the surface of a pile aided by reflected heat from hot brickwork, air for combustion coming through the grates.<sup>3</sup> Forced draft was later added for higher capacity. Many of these earlier furnaces are still in use.

**Hearth Type.** To overcome objectionable features arising from the clogging of grates, and to reduce the blow-over of excessive amounts of fuel, the hearth or grateless

<sup>1</sup> Gilg, F. X., *loc. cit.*

<sup>2</sup> Moisture content usually varies between 45 and 55 per cent, depending on the type and efficiency of the squeezing equipment.

<sup>3</sup> See Kern, E. W., Bagasse Furnaces, *Trans. ASME*, vol. 61, pp. 685-691, 1939, for a description of bagasse furnaces.

type of furnace was developed. Retaining the essential feature of burning the bagasse on the top of a pile, air for combustion was admitted through tuyères in the vertical walls surrounding the hearths.

**Horseshoe Furnace.** The Cook, or horseshoe, furnace was arranged in multiple units under the boilers to minimize drop in steam pressure during cleaning. The horseshoe shape was chosen to facilitate cleaning through one door located at the front of each hearth. The horseshoe furnace remains the basis of most of the better designs of bagasse furnace.

**Ward Furnace.** Today, the Ward single-pass furnace or a modification of the original is accepted as standard for the combustion of bagasse. The principal features of this furnace are the elimination of costly arches over Dutch ovens, a reduced amount of costly brickwork, and the absence of grates and their maintenance. From an operating standpoint, the furnaces can be fired continuously because the refuse

**Table 5-21. Integral-furnace Boiler-burning Bagasse<sup>1</sup>**  
(Test results and heat balances)

Rate of steam flow. . . . .	A	B	C	D
Steam flow, lb/hr . . . . .	56,500	70,400	75,600	86,500
Bagasse, lb/hr . . . . .	27,500	33,000	35,000	41,300
Bagasse, lb/sq ft/hr . . . . .	291	349	370	437
CO <sub>2</sub> at air-heater outlet, per cent . . . . .	10.5	12.0	12.7	13.2
Temperature at air-heater outlet, deg F . . . . .	505	520	516	530
Draft at boiler outlet, in. H <sub>2</sub> O . . . . .	1.9	2.1	2.3	3.1
Draft at air-heater outlet, in. H <sub>2</sub> O . . . . .	5.2	5.8	6.3	8.2
Pressure in windbox, in. H <sub>2</sub> O . . . . .	1.7	2.5	3.1	3.7
Refuse in stack discharge, lb/hr . . . . .	155	272	392	733
Refuse in stack discharge, per cent of fuel . . . . .	0.564	0.824	1.120	1.178
Combustible content, refuse, per cent . . . . .	40.5	24.0	31.9	26.7
Loss to refuse, per cent. . . . .	0.9	0.7	1.0	1.8
Heat balance:				
Efficiency of unit, per cent . . . . .	60.6	63.0	63.7	62.2
Loss, dry products combustion, per cent . . . . .	13.3	11.3	10.5	11.0
Loss, water in fuel, and air, per cent . . . . .	23.9	24.0	23.9	24.2
Loss, unburned combustible, per cent . . . . .	0.9	0.7	1.0	1.8
Loss, CO in flue gases, per cent . . . . .	0.0	0.0	0.0	0.0
Loss, radiation, per cent . . . . .	1.3	1.0	0.9	0.8

PROXIMATE ANALYSIS: Moisture, 52.25 per cent; volatile, 40.2 per cent; fixed carbon, 5.9 per cent; ash, 1.65 per cent, Btu, 3,900 per lb.

<sup>1</sup> GILG, F. X., Utilizing Bagasse as Fuel, *ASME Tech. Paper* 48-S-3, spring meeting, New Orleans, March, 1948.

can be removed while the boiler is in service; there is no slag in the combustion chamber and the labor and delay for its removal are therefore saved.

Figure 5-2 shows the general shape of the Ward furnace as applied to a modern Stirling boiler. There is usually some carry-over of burning embers into the boiler passes at high rates. These can be collected in hoppers for periodic removal or mechanical return. Babcock & Wilcox<sup>1</sup> has also designed a furnace adding secondary pinhole grate surface behind the Ward-type furnace for the collection and final burning of carry-over.

**Operating Procedure.** Bagasse is dropped on the hearth of Ward furnaces through a chute in the front wall, forming a conical pile about 5 ft high. Hot air for combustion is forced horizontally into the base of the pile from air slots in a base plate completely surrounding the hearths, which may be 5 ft wide and 7 ft long and have rounded corners. Air for combustion is also forced into the pile higher up through three rows of tuyères. The feed of bagasse is continuous, falling on a pile in each

<sup>1</sup> GILG, F. X., *loc. cit.*

hearth, igniting from the reflected heat of the brickwork. The bagasse burns vigorously on the surface of the piles.

**Operating Results.** In the older style plants, efficiencies generally range from 50 to 60 per cent with "radiation and unaccounted" losses as high as 20 per cent. The moisture and hydrogen loss is usually in the order of 20 to 25 per cent. Radiation was high because of the low rating per unit area of brickwork with natural draft, particularly. Low boiler efficiency, resulting from burning wet bagasse, does not present a problem where the plant has more bagasse than is needed, as, on the other hand, an excess of bagasse would present a problem.

However, where the sugar mill refines its own sugar, distills alcohol, or needs fuel for other purposes, higher efficiencies may be desirable. In such instances, the need will be met by such modern integral-furnace boiler design as that of Babcock & Wilcox, as described by Gilg.<sup>1</sup> As is shown in Table 5-21, efficiencies with such a unit are 60 to 64 per cent even while burning fuel with a moisture content of 52.25 per cent.

### STRAW

A typical analysis of straw, which is sometimes burned as a fuel, is as follows:

Carbon, per cent	36 00
Hydrogen, per cent	5 00
Oxygen, per cent .	38 00
Nitrogen, per cent	0 50
Moisture, per cent	15 75
Ash, per cent . .	4 75
Heat value, Btu...	5,400

<sup>1</sup>*Loc. cit.*

## CHAPTER 6

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### MANUFACTURED SOLID FUELS, COKES, AND BRIQUETTES

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## METHODS OF MAKING COKE<sup>1</sup>

Coke is the fused, cellular, porous structure that remains after free moisture and the major portion of the volatile matter have been distilled from bituminous coal and other carbonaceous material by the application of heat in the absence of air or the presence of a limited supply.

When coking coal is heated at a uniformly increasing temperature, free moisture is driven off first, followed by combined moisture and carbon dioxide resulting from the decomposition of the more unstable groups of the coal itself. Between 300 and 440°C, the coal begins to soften. As the temperature continues to rise, plasticity reaches a maximum and then decreases until the plastic mass becomes rigid again. Volatile products are actively evolved during the plastic stage, causing more or less swelling of the mass, ultimately resulting in the cellular porous structure of the coke. Final rigidity is attained at between 450 and 500°C, after which the character of the coke continues to change owing to further devolatilization and to shrinkage.

Upon the basis of carbonization temperature, coke falls into three broad classes as follows:

1. *High-temperature coke*, carbonized at temperatures ranging from 900 to 1200°C, generally at 1100°C. During high-temperature carbonization, the volatile products undergo secondary decomposition, yielding a relatively large quantity of gas having a low heating value, a minimum of tar, and a coke residue containing a graphitic form of carbon.

2. *Low-temperature coke*, carbonized at temperatures below 750°C, generally between 500 and 600°C. During low-temperature carbonization, the secondary decomposition of the volatile matter is at a minimum, yielding a relatively small quantity of gas having a high heating value, a maximum of tar, and a coke residue consisting of an active form of carbon.

3. *Medium-temperature coke*, carbonized at temperatures ranging between 750 and 900°C, generally at 850°C. During medium-temperature carbonization some secondary decomposition of the volatile products occurs. The yield and character of the tar and coked residue fall between those of high- and low-temperature carbonization.

High-temperature coke may be produced in beehive ovens, slot-type ovens, sole-heated ovens, and a variety of retorts.

**Beehive coke ovens** are hemispherical structures built of firebrick. Approximately 12 ft in diameter and 8 ft high, they frequently are built in long double rows with as many as 100 ovens in a row. Each oven carbonizes a charge of 5 to 6 tons in 48 to 72 hr. Provisions are made for charging coal through a hole in the top, and the coal is leveled off to a depth of about 2 ft through a door in the front. This door also serves for admitting air and removing the coke. Combustion takes place largely above the fuel bed, and the products of combustion are vented through the top. The coking action is downward. As few beehive ovens are equipped for recovering volatile products, all the volatile chemical products are lost.

<sup>1</sup> By L. L. NEWMAN, Gas Engineer, U.S. Bureau of Mines, Washington, D.C. References used by Newman in compiling résumé: "Chemistry of Coal Utilization," Vol. 1, Lowry, H. H., Editor, Chap. 21, Industrial Coal Carbonization, by Fred Denig, pp. 774-833, John Wiley & Sons, Inc., New York, 1945. GENTRY, FRANK M., "The Technology of Low-temperature Carbonization," The Williams & Wilkins Company, Baltimore, 1928. "Low-temperature Carbonization of Utah Coals," Report of the Utah Conservation and Research Foundation to the Governor and State Legislature of Utah, May, 1949. RUSSELL, CHARLES C., The Selection of Coals for the Manufacture of Coke, *AGA, Proc.*, 1947, pp. 733-756. SAVAGE, PHILIP S., Production of Metallurgical Coke and Resultant Coal Chemicals, *Steel*, vol. 124, Part I, No. 18, pp. 94-104; May 2, 1949, Part II, No. 19, pp. 117-132, May 9, 1949; Part III, No. 20, pp. 102-114, May 16, 1949.

In modern **slot-type ovens** or retorts the chemicals are recovered. Slot-type ovens are long, narrow, rectangular chambers 35 to 45 ft long, 12 to 18 ft high, and 14 to 18 in. wide, with a horizontal taper of about 3 in. They can carbonize a charge of 15 to 20 tons of coal in 14 to 18 hr. The ovens are built in batteries of 25 to 75, with walls of silica brick and vertical heating flues between them. Coal is charged from the top, and coke is discharged at the wide end of the oven by means of a pusher acting at the narrow end. Slot ovens constructed by different builders vary principally in the design of the heating flues and the methods of supplying the fuel and recovering waste heat.

**Sole-heated ovens**, originally developed for coking petroleum residues, are built in batteries of arched rectangular firebrick chambers, about 30 ft long and  $7\frac{1}{2}$  ft wide, 4 ft high at the top of the arch, and 2 ft high at the sides. Coal is charged through holes in the top, and coke is removed through openings at the ends. Heat is applied through flues underneath the silica-brick floor of the oven. A charge of about 5 tons of coal leveled off at a depth of about 12 in. is normally carbonized in 8 hr.

Retorts may be horizontal, inclined, or vertical. Early retorts were built of cast iron, but modern ones are usually of silica or firebrick.

**Horizontal retorts** and **inclined retorts** have a semicylindrical or D-shaped cross section varying from 14 by 24 to 16 by 28 in. and are set in benches of 6 to 12. Stop-end retorts (horizontal only) have one end permanently closed, and the charge of coal is admitted and the coke removed through the opening at the other end. Stop-end retorts are 10 to 12 ft long and carbonize a charge of 250 to 400 lb of coal in 4 to 6 hr. Through retorts, having openings at both ends, vary from 11 to 22 ft in length and carbonize charges of 400 to 1,000 lb in 4 to 12 hr.

**Vertical retorts** are usually 25 ft high with rectangular or elliptical cross sections ranging from 33 by 10 to 103 by 10 in., with enough taper to permit free removal of coke. Intermittent vertical retorts carbonize 2,000 to 2,400 lb of coal in about 12 hr. Coal from an overhead bin is fed into continuous vertical retorts through openings at the top, and coke is extracted continuously at the bottom. To increase the gas yield, a controlled amount of steam is introduced at the base of the retort. The steam reacts with the coke to produce water gas. Steaming reduces the yield and quality of the coke in direct proportion to the amount of steam admitted.

**Medium-temperature coke** is produced in coke ovens similar in design to high-temperature slot-type ovens, but with narrower chambers. No medium-temperature ovens have been reported operating in the United States, but several batteries have been installed in Europe.

**Low-temperature coke** may be produced in a variety of types and designs of retort. Low-temperature carbonization plants may be heated internally or externally or by a combination of both. When heated internally, the carrier fluid may consist of hot gases or superheated steam. The retorts may be of metal or refractory material, and they may operate intermittently or continuously. The most successful commercial low-temperature plant operating in the United States uses the Disco process, a modification of the Wisner process. In this process the coal is heated to 315°C in roasters and partly oxidized. It is then mixed with a definite proportion of breeze and carbonized in inclined rotating steel cylinders heated externally. Coke in the form of rough spheres is removed at the lower end of the cylinder.

On the basis of use, coke may be classed as blast-furnace, foundry, water-gas, gas-producer, or domestic.

**Blast-furnace coke** should have mechanical strength to support the burden in the blast furnace. It should have a uniform size and be free from breeze and therefore should be hard enough to resist degradation in the course of rough handling. Generally it should be uniform in physical and chemical composition. The consensus



among blast-furnace operators is that uniformity of quality is more important than the ash, sulphur, and phosphorus content, although these should preferably be as low as possible.

**Foundry coke** should be dense, blocky, and fairly large, with low ash, sulphur, and phosphorus content. It must be strong enough to support the burden and resist the abrasion of the pig iron and scrap in the cupola.

**Water-gas coke** is preferred 2 to 4 in. in size. It should be strong enough to permit handling with a minimum of degradation, for breeze in the generator is objectionable. It should be low in ash content, with a lower limit of 2400°F in ash-fusion temperature for proper control of clinker.

**Gas-producer coke** is generally smaller than water-gas coke. It should be free from breeze and closely sized.

**Domestic coke** should have a low ash content, high ash-fusion temperature, and high density. It should be carefully sized and dustproofed before delivery to the consumer.

The principal sources of blast-furnace, foundry, water-gas, gas-producer, and domestic coke in the United States are slot-type ovens. Beehive ovens are pressed into service during periods of peak demand for metallurgical coke. Retort coke is used for water-gas production, principally where high-capacity operation is not the prime consideration. Retort coke also is used as domestic fuel.

Outside the United States, where central heating is less prevalent, the general preference has been for more active fuels for domestic heating. Frequently coupled with a lack of suitable high-temperature coking coal, this resulted in the development of a variety of low-temperature carbonization processes. The coke or char has a higher content of volatile matter and is more easily ignited but nevertheless burns smokelessly. Several medium-temperature carbonization plants operating in Europe supply a product intermediate in quality between high- and low-temperature coke, which also is desirable as a smokeless fuel. The medium-temperature plants, however, require coking coal for proper operation.

### COKE FROM COAL<sup>1</sup>

**Historical.** Coke has been known to mankind for more than 2,000 years and was used to a limited degree through the Middle Ages. It was not until the sixteenth century, however, that much reference to coke production is found. At that time, coal was coked in piles covered over with dirt, wet straw or leaves, or wet coke breeze. Flues were formed in the pile by large lumps of coal or by withdrawing wooden posts around which the coal had been piled. Coke yield was about 33 per cent of the coal carbonized. Later, a permanent refractory chimney was used in the center of the pile.

Gradually, brick walls were used to confine the pile, and air ports and chimney flues were built into the walls. The top of the coal was covered with fine wet coke or dirt. Coking time was about 8 days, and 2 more days were necessary for cooling before drawing the coke by hand. The coke yield gradually increased to about 55 per cent of the coal carbonized.

From this, the beehive oven was developed, which was essentially a refractory container in which the coking pile was placed. Until 1893, all coke in the United States was made in beehive ovens. At that time, recognition of the tremendous waste of valuable by-products in beehive coking led to the development of the now dominant by-product oven. However, as their progress was slow, beehive-coke production continued to increase until 1916, when 35,464,000 tons, representing 65 per cent of the total United States production, were so made. Since 1916, oven coke

<sup>1</sup> Ess, T. J., *The Modern Coke Plant*, *Iron Steel Engr.*, 1948.

Table 6-1. 1938 and 1940 to 1946 World Production of Coke<sup>1</sup>  
(In metric tons)

Country <sup>2</sup>	1938	1940	1941	1942	1943	1944	1945	1946
Australia:								
New South Wales.....	1,153,670	1,292,484	1,738,864	1,644,897	1,592,325	1,402,310	1,061,822	b
Queensland.....	31,481	21,961	30,991	22,529	15,304	14,657	15,903	13,757
Victoria.....	4,894,980	3,945,280	4,425,180	4,407,080	4,410,940	2,047,280	2,060,160	3,856,729
Belgium.....	1,808,588	9,912	21,068	2,536,165	2,709,354	3,217,107	3,008,050	2,585,493
Canada.....	237,394 <sup>a</sup>	2,321,775	2,431,942	3,888,734 <sup>d</sup>	3,379,822 <sup>d</sup>	302,466 <sup>d</sup>	44,000	95,910
China.....	11,630 <sup>e</sup>	3,733,000	3,696,000	3,889,000	4,280,000	4,528,000	2,505,972	b
Czechoslovakia.....	2,766,000	3,733,000	3,696,000	3,889,000	4,280,000	4,528,000	2,505,972	b
France.....	7,636,150	5,161,570	4,892,860	5,008,360	4,989,580	2,908,655	49,866,000 <sup>f</sup>	4,959,889
Germany <sup>3</sup> .....	40,404,082	46,931,593	47,636,121	47,996,026	49,457,000 <sup>f</sup>	49,866,000 <sup>f</sup>	3,534,000 <sup>f</sup>	b
Greece.....	3,107,000	1,762,293	3,264,830	3,241,439	3,304,000 <sup>f</sup>	3,534,000 <sup>f</sup>	14,307,360	b
Great Britain <sup>4</sup> .....	13,031,396	15,597,384	14,780,479	15,139,145	14,683,955	14,307,360	14,210,170	14,211,085
India.....	1,738,178	1,872,810	1,999,436	1,882,533	1,578,137	1,406,299	b	b
Indo-China, French.....	3,503	2,600	b	4,400	5,300	2,700	b	b
Italy.....	1,739,417	1,987,903	1,833,388	1,668,188	2,000,000 <sup>a</sup>	3,759,000	b	b
Japan <sup>5</sup> .....	3,724,000	4,591,000	5,222,000	5,842,000	4,801,000	733,216	91,541 <sup>f</sup>	40,000 <sup>f</sup>
Korea (Chosen).....	3,377,937	3,661,961	399,860	582,918	851,307	b	b	b
Netherlands.....	3,158,065	• 2,367,000	b	1,937,000 <sup>f</sup>	1,901,000	b	b	b
New Caledonia.....	49,875	69,762	99,700	83,661	b	b	b	b
Poland.....	2,523,290	b	b	2,300,000	2,300,000	b	1,743,239	2,146,852
Rumania.....	86,030	85,623	84,741	86,115	84,212	b	b	b
Southern Rhodesia.....	47,986	59,060	81,016	71,402	78,566	79,857	85,103	b
Spain.....	571,469	839,744	753,108	814,355	801,122	862,574	909,000	704,600
Sweden.....	112,107	100,753	b	b	81,617	b	b	b
Turkey.....	84,930	60,192	61,086	81,950	90,000	212,000	59,883	43,003
Union of South Africa.....	163,315	221,885	226,503	232,498	240,724	176,524	176,524	b
U.S.S.R.....	20,700,000	16,500,000	b	6,085,000 <sup>a</sup>	7,801,000 <sup>a</sup>	9,915,000 <sup>a</sup>	13,000,000 <sup>a</sup>	61,060,636
United States.....	29,479,553	51,774,699	59,135,960	64,018,735	65,023,091	67,165,627	61,060,636	53,068,078
Total <sup>6</sup> .....	139,837,000	164,901,000	167,204,000	170,744,000	174,114,000	173,435,000	114,948,000	117,438,000

<sup>1</sup> Compiled by ROBERTS, P., in "Minerals Yearbook," U.S. Bureau of Mines, Coke and Coal Chemicals Preprint, p. 45, 1946.<sup>2</sup> In addition to countries listed, coke is produced in Mexico and New Zealand, but data are not available.<sup>3</sup> Data not available.<sup>4</sup> Exports.<sup>5</sup> Data represent areas designated as Free China during the period of Japanese occupation.<sup>6</sup> Beginning October, 1939, Silesian production included.<sup>7</sup> Coal year ended Mar. 31 of year stated.<sup>8</sup> In Great Britain, production of gas house coke, not included, is especially important and was 10,770,130 tons in 1938, and averaged 11,000,000 tons per year for 1940 to 1944, inclusive. Data for 1945 and 1946 are not available.<sup>9</sup> Estimate.<sup>10</sup> Preliminary data for fiscal year ended Mar. 31 of year following that stated.<sup>11</sup> South Korea only.<sup>12</sup> Production of Siberia and Urals only.<sup>13</sup> Estimated by author. Excludes estimates for Mexico and New Zealand.

(by-product) capacities increased until, as of Dec. 31, 1946, they represented 87.5 per cent of the total coke-from-coal capacity of the United States.

**Table 6-2. Production of Coke in the United States by Types of Equipment Used,<sup>1</sup> 1946**

Type of coke	Ovens in existence Dec. 31, 1946	Oven capacity Dec. 31, 1946	Actual production, 1946
Oven (by-product) coke <sup>a</sup> . . . . .	14,494	71,112,600	53,929,447
Beehive coke . . . . .	12,864 <sup>b</sup>	8,427,000	4,568,401
Subtotals . . . . .	27,358	79,539,600	58,497,848
Retort coke:			
Horizontal retorts . . . . .	1,559	652,100	278,170
Vertical retorts and gas ovens . . . . .	589	956,400	475,165
Subtotals . . . . .	2,148	1,608,500	753,335
Medium- and low-temperature cokes . . . . .	31	190,100	131,194
Subtotal, cokes from coal . . . . .		81,338,200	59,382,377
Petroleum residuals:			
Petroleum coke . . . . .		. . .	2,124,200
Coal-tar-pitch coke . . . . .			92,000

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, Preprint, 1946.

<sup>a</sup> Oven coke, produced in vertical-slot high-temperature ovens, was formerly called by-product coke.

<sup>b</sup> Located in 68 plants, principally in Pennsylvania.

### CARBONIZATION OF COAL<sup>1</sup>

Warner<sup>1</sup> has made the following valuable deductions outlining the evolution of the volatile matter in coal:

1. If the removal of volatile matter from coking coal were the only consideration, the high heats commonly used in carbonization are unnecessary; i.e., practically all the volatile matter in coal could be driven off below 1050°F (566°C), but the necessary conditions for accomplishing this (prolonged slow heating, for example) destroy the coking properties. The reasons for high temperatures lie in the necessity for producing a special type of solid residue and for completing carbonization within a reasonable time.

2. Although the thermal decomposition of tar and other materials in the oven or retort increases the gas yield, the increase in gas is far from being proportional to the degree of decomposition, since carbon is one of the main products of such a decomposition.

3. The less the cracking and the more the distillation of condensable hydrocarbons occurs the less will be the intensity of heat required to drive off the volatile matter of coal. In other words, considerable heat is absorbed by cracking reactions, and if this heat could be conserved it would be possible to decrease the amount of heat required for carbonization.

**Table 6-3. Typical Production from 1 Ton of Coal<sup>1</sup>**

(In by-product coke practice)	
Furnace coke, lb . . . . .	1,200-1,300
Nut coke, lb . . . . .	100-200
Coke breeze, lb. . . . .	80-150
Coke-oven gas, cu ft . . . . .	9,900-11,500
Tar, gal . . . . .	8-12
Ammonium sulphate, lb . . . . .	20-28
Liquor, gal . . . . .	12-35
Light oils, gal . . . . .	2½-4

NOTE: These yields depend to a great degree on the coal used, the coking temperature, and the method of recovery.

<sup>1</sup> *Iron Steel Engr.*

sometimes will increase greatly the strength and density of the resultant coke residue.

The application of these simple fundamental considerations has a marked effect on the various factors in the products of coking.

<sup>1</sup> WARNER, A. W., *AGA, Proc.*, vol. 5, p. 928, 1923.

4. The less the heat through which the noncondensable hydrocarbons must pass in leaving the oven or retort the richer will be the gases. In other words, the reactions of thermal decomposition or cracking speed up markedly at high temperatures, and therefore the lower the temperature or the shorter the time of contact between these hydrocarbons and hot coke or the heated oven walls the less will be the cracking. High temperatures and long time of contact in practice are also responsible for troublesome naphthalene deposits. However, a very small amount of carbon deposited from the thermal decomposition of the gases

**Differences between High- and Low-temperature Carbonization.**<sup>1</sup> High-temperature carbonization is usually carried out with a final temperature of the coked charge of from 1800 to 2100°F (982 to 1149°C). In low-temperature carbonization, on the other hand, the maximum temperatures to which the charge is subjected in most instances are from 1000 to 1400°F (538 to 760°C), and many of the features of the process are different from those obtaining in high-temperature carbonization.

In the first place, with low wall temperatures employed in low-temperature carbonization, the rate of heat transfer is very slow, and the cementing materials present in the coal are distilled off, leaving a relatively noncoherent granular coke. The low rate of heat transfer also necessitates either a very thin coal charge, agitation of the coking mass, or contact with hot gases in order to obtain reasonable capacity from the retorts. Oversized retorts must be provided, since there is considerable tendency for swelling.

In low-temperature carbonization, the volatile hydrocarbons distilled out of the coal are not subjected to high temperatures in passing through the coke or up along the retort walls, and consequently they are decomposed thermally only to a very small extent. The products of carbonization, as shown by Table 6-4, differ markedly from

**Table 6-4. Comparison of Products from High- and Low-temperature Carbonization<sup>1</sup>**

Product	High-temp carbonization	Low-temp carbonization
Coke:		
Lb/100 lb coal	65-70	75-80
Per cent volatile matter	1-3	7-15
Gas:		
Cu ft/ton	10,000-13,000	4,000-6,000
Btu/cu ft	530-600	700-900
Light oil and tar, gal/ton	10-17	20-40
Ammonium sulphate, lb/ton	24-26	12-15

<sup>1</sup> HASLAM, ROBERT T., and ROBERT P. RUSSELL, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1925.

those obtained at higher temperatures, not only in quantity but in quality as well. The coked residue from low-temperature processes, representing from 75 to 80 per cent of the coal charged, is friable and porous, and contains from 7 to 15 per cent volatile matter. Such coke ignites easily, however, and burns without smoke. The gas yield is low, only from 4,000 to 6,000 cu ft per ton of coal carbonized, but, owing to the small degree of thermal decomposition of the hydrocarbons, it is of much higher heating value than ordinary coal gas. Although ammonia production is less, high yields of tar and liquid fuels are obtained; these differ greatly in composition from the products of high-temperature carbonization and consist largely of phenols and paraffin hydrocarbons.

## TYPES OF COKE<sup>2</sup>

### Beehive Coke

The modern beehive oven is essentially hemispherical in shape, approximately 12 ft in diameter and 8 ft high. It is built of highly refractory brick, covered over with loam. An opening in the top of the oven permits the charging of coal and the escape of waste gases, while a door is left at the bottom of the oven for watering and drawing the coke, and for admitting air for combustion.

<sup>1</sup> HASLAM, ROBERT T., and ROBERT P. RUSSELL, "Fuels and Their Combustion," p. 667, McGraw-Hill Book Company, Inc., New York, 1925.

<sup>2</sup> Ess, T. J., *Iron Steel Engr.*, pp. C3-C5.

Mechanization of beehive ovens in some cases may include a charging car running along the tops of the ovens, a drawer or pusher car running along one side of the ovens, and a car-loading conveyor along the other side of the ovens.

Reclamation of some of the gases driven off is practiced in some plants. One method is to gather the gases in a common flue for use under boilers; in other instances, the expelled gas is burned in flues under the oven floor to provide heat for the coking process.

**Operation of Beehive Ovens.**<sup>1</sup> When the beehive oven is hot and ready for charging, coal is charged and leveled to a depth of 2 to 2½ ft, and the door is bricked up almost to the top. The charging reduces oven-wall-surface temperature to some 600 to 700°F, but heat stored in the brickwork soaks in, and the temperature gradually rises.

As heat from the oven brickwork reaches the coal, the volatile matter begins to distill off and soon ignites (at about 1200°F), burning with the air brought in through

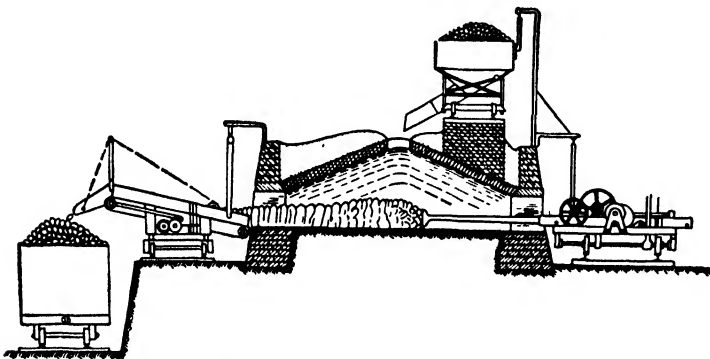


Fig. 6-1. Cross section through a mechanized beehive coke oven, showing charging car, pusher, and car-loading conveyor. (*Ess, Iron and Steel Engineer*, 1948.)

the door. The volume of volatile matter driven off gradually increases, holds steady for awhile, and then drops off. The opening at the top of the door must be gradually closed as the volatile decreases, in order to regulate combustion and maintain oven temperatures at a maximum of 2000 to 2200°F. Too much or too little air lowers the temperature. The correct amount is 0.8 to 0.9 of the quantity required for complete combustion of the gas driven off. Gas leaving the oven should contain 2 to 4 per cent carbon monoxide and less than 1 per cent oxygen.

Coking time depends principally on the depth of the coal, with coking proceeding from the top of the coal downward. A depth of about ½ in. is coked per hour, so that coking time is usually 48 to 72 hr.

When evolution of volatile matter stops, as is shown by subsidence of smoke issuing from the oven top, the coke is sprayed with water and removed from the oven. During quenching, oven-wall temperature is reduced to 800 to 900°F.

Coke yield is about 65 per cent of the coal charged. Beehive ovens will coke 2 to 2½ lb of coal per hr per sq ft of oven-floor area.

Beehive coke is silvery gray in color and has a long columnar structure.

#### By-product Coke<sup>2</sup>

Practically all the by-product coke ovens now operating in the United States are of the vertical-slot type. The individual ovens are rectangular chambers 30 to 45 ft

<sup>1</sup> Ess, T. J., *Iron Steel Engr.*, pp. C3-C5.

<sup>2</sup> Ess, E. J., *Iron Steel Engr.*, pp. C9-C12.

long, 6 to 15 ft high, and 14 to 22 in. wide. The trend has been toward high ovens so as to obtain greater capacity with minimum costs of construction and operation.

The smaller 14-in. oven, with its lower coking time, is used in a few cases where it might possibly benefit coke quality from inferior coals by reducing overcoking.

The width of ovens tapers off  $2\frac{1}{2}$  to 4 in. from coke side to pusher side according to the characteristics of the coal to be coked. The greater tapers are used with coals of marked expanding tendencies.

In the roof of each oven are three or four charging holes 14 to 16 in. in diameter, normally closed with a cast-iron frame and cover. The oven roof also carries, at

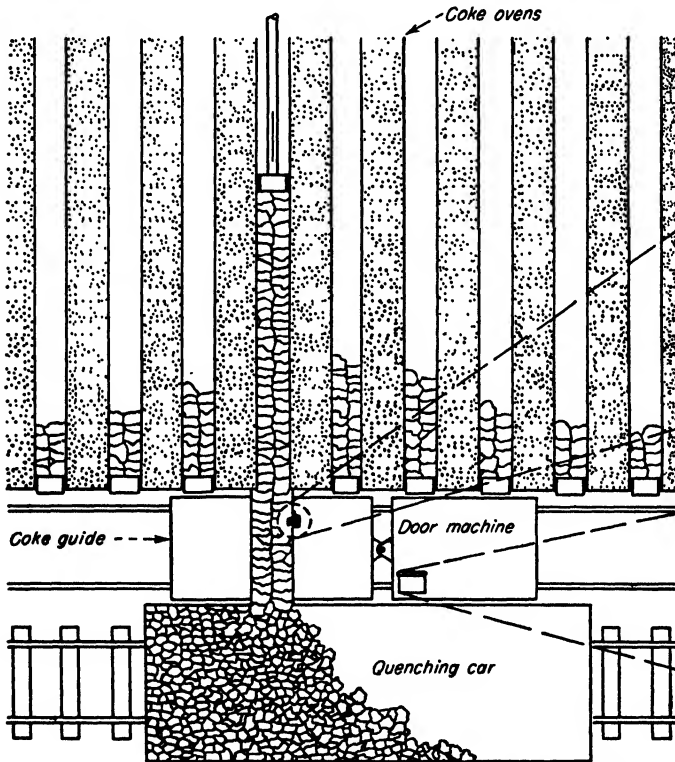


FIG. 6-2. Plan view of by-product coke-oven battery, showing coke being pushed from vertical slot retort (top to bottom of figure). Small squares at sides of coke retorts are heating flues.

either one or both ends, an offtake about 14 in. in diameter which leads to the ascension pipe, which in turn connects into the connecting main.

The ends of the ovens are closed by refractory-lined doors of welded-steel and cast-iron construction. In the older plants, these doors and door frames were designed with a recess so that they could be luted with clay to make a tight closure. More recently, self-sealing doors have been adopted wherein a flexible steel plate carrying a sealing edge is incorporated in the door so that it will conform to irregularities in the door jamb. Each door is held in place by latch bars and has guides and hooks for lifting it. The doors on the pusher side have a leveler door to permit entry of the leveling bar.

Ovens are grouped side by side, on centers of  $3\frac{1}{2}$  to 4 ft, to comprise a battery which may contain as many as 87 ovens. In each wall between adjacent ovens are some 28 or 29 vertical heating flues on centers of 15 to 18 in. These flues are approximately 10 by 16 in. and extend to almost the entire height of the oven chamber. The walls separating the oven chamber from the heating flues are 4 to 6 in. thick, with tongue-and-groove joints to prevent leakage. Thus each row of flues serves to heat two adjacent ovens, except at the end of the battery. Inspection holes are provided for observation of heat distribution.

Beneath the oven chamber and heating flues are regenerator chambers containing checkerwork which reclaims heat from the outgoing waste gases and, upon reversal, gives up heat to the incoming combustion air. If a lean flue gas (blast-furnace or producer gas) is used to heat the ovens, it is also preheated in the regenerators, in order to obtain the necessary flame temperature for rapid schedules. In such cases, the regenerative system must be designed to permit preheating of both air and gas. Checkerwork is usually made up of slotted fire clay shapes, with  $\frac{5}{8}$ -to  $1\frac{1}{2}$ -in. flues and walls  $\frac{5}{8}$  to 1 in. thick. These shapes are piled to a height of 5 or 6 ft. For each oven, the checkerwork provides 10,000 to 11,000 sq ft of heating surface and about 35,000 to 50,000 lb of regenerative material. The arrangement of oven-heating flues and regenerators and the path of gas flow through them vary somewhat with the designs of the various builders.

**Oven Manufacturers.** About 97 per cent of the total coking capacity in the country is supplied by the four basic designs of **Koppers**, **Koppers-Becker**, **Wilputte**, and **Semet-Solvay**.

The **Koppers** oven is a double-divided design, wherein all vertical heating flues in each wall connect at the top into a single horizontal flue. The regenerator chambers beneath the ovens are divided into halves. The ovens are heated by burning gas in the vertical flues, the gases flowing upward in the flues in one-half of the oven wall, through the horizontal flue, and down through the vertical flues in the other end of the wall. This flow is reversed regularly.

In the **Koppers-Becker** design, the gases from four to six vertical flues are gathered into a short flue and led through a crossover flue of inverted U shape over the top of every other oven and down through four to six vertical flues on the other side. Thus each set of four to six vertical flues is separated from each other set. There may be five to eight of these sets across the length of the oven. This flow is reversed regularly.

The **Wilputte** oven is a four-divided design. It uses the same flow principles as the **Koppers** design, except that the horizontal flue is divided in half so that there are four zones instead of two. Gas flows in the two outer zones in the same direction, with opposite flow in the two inner zones. The flows are periodically reversed.

Most of the **Semet-Solvay** installations have oven batteries employing horizontal heating flues, wherein gas is introduced at one end and waste gas drawn off at the other end, with periodical reversal of flow. Several batteries, however, have been constructed with vertical flues. These are four-divided designs but differ from upflow zones, and the two downflow zones are placed alternately across the length of the oven wall.

**General Operation and Results.** Ovens are usually charged with coal to a level of 12 to 14 in. from the oven roof, thus filling 91 to 92 per cent of the total oven volume. Modern units will therefore hold 700 to 750 cu ft of coal, which, at a normal bulk density of 50 lb per cu ft, equals 17.5 to 18.8 net tons of coal per oven, or a coke production of 13 to 14 tons per oven per charge.

**Coking time** depends on the width of the oven, temperature of oven walls, kind of coal, and the fineness and moisture content of the coal. In general, ovens are designed for a standard coking velocity of 1 in. per hr (coking velocity = oven width in inches

+ coking time in hours). In practice, coking velocities of 1.2 in. per hr or even higher are often used. Actually, with wall temperatures equal, a narrow oven will operate on a proportionately shorter coking time than a wide oven. For example, with equal temperatures, a 14-in. oven will operate on a coking time of about 55 per cent of that of a 20-in. oven. To coke coal in the two ovens at the same velocity, the wider oven must have a higher wall temperature.

**Gross coking time** is the time elapsed between two successive pushings of the same oven, while **net coking time** is the time of actual coking, usually amounting to about 96 per cent of the gross time.

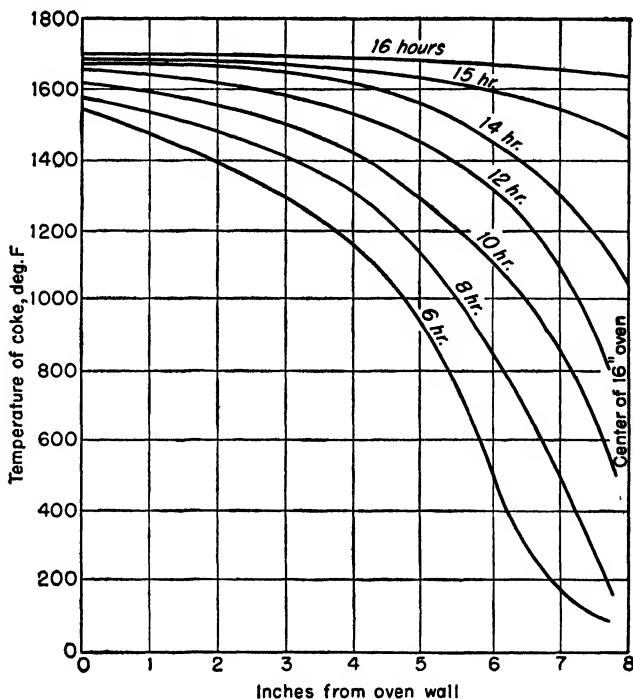


FIG. 6-3. Temperature distribution in coal charge at various stages of the coking cycle. (*Ess, Iron and Steel Engineer*, 1948.)

The **capacity of an oven** may range from 2 to  $2\frac{1}{2}$  lb of coal coked per hr per sq ft of coal-covered wall area, the narrower ovens running to the higher values.

A modern oven under normal operation will produce about 0.75 ton of coke per hr.

**Charging and Pushing Schedule.** An important factor in coke-oven operation is the cycle of charging and pushing the ovens. It is generally agreed that the adjacent ovens on both sides of the oven being pushed should be as close as possible to the same age or degree of coking. To this end, various pushing schedules have been devised, some of which become rather complicated and some of which have even been patented.

In most schedules, the ovens of a battery (or in some cases, two or three batteries) are divided into a number of groups, each group usually consisting of 5, 7, or 9 consecutive ovens. The number of such groups in a battery is, of course, the total number of ovens divided by the number in each group. Pushing then proceeds on the first oven in each group, then on the third in each group, then the fifth, and so on through the odd numbers. When the odd numbers in each group have been covered,



the second in each group is pushed, followed by the ensuing even numbers. The "9" series shows the smallest difference in age of adjacent ovens, and this series is thus probably in widest use.

Several schedules include a short idle period for each oven after pushing to permit decarbonizing of oven walls. This is particularly important with coals of high volatile content.

### Heating By-product Coke Ovens<sup>1</sup>

By-product coke ovens are heated by burning fuel gas in vertical heating flues adjacent to the coal-containing ovens or slots. In plants where the oven mat sits directly upon the ground, the gas used for heating the ovens is distributed to the flues by silica-brick ducts or "gun brick" passing under the vertical heating flues in each oven wall. Gas is admitted to the individual vertical heating flues through a brick nozzle. Gas is proportioned to each flue by varying the area of the port in this nozzle.

In batteries of the elevated or underjet type, gas is distributed through steel pipes installed in the basement. In the pipe to each flue, a regulating orifice is installed, and gas is proportioned to each flue by changing the size of this orifice. The underjet design offers more accurate control of heating, with greater ease of regulation, because the gas is metered to each vertical flue at constant temperature and pressure, while in the older-style gas duct the temperature and pressure vary widely from end to end.

Fuel gas is distributed to the ovens through mains and manifolds suitable for the fuel used. Coke-oven gas is usually brought through one or two 18- to 24-in. mains that run the entire length of the battery. Two mains, one on each side of the battery, are used for the gun-brick type of distribution, while one main serves for the underjet type, feeding into 3- to 4-in. leads which run across the battery under each flue wall and feed  $\frac{3}{4}$ -in. risers to each heating flue. A reversing cock and a regulating device are installed in the lead for each oven.

With blast-furnace gas, the main may initially be 36 to 40 in. in diameter and be stepped down to 24 to 30 in. A 6-in. connection may be used to feed the bus flue of each oven, from where the gas flows up through the regenerators and into the flues.

The reversing cocks installed on the fuel-gas lines and the valves on the waste-heat exits and air inlets are all operated as a unit. The valve-operating levers are attached to reversing rods which run the length of the battery and are operated automatically by a reversing machine. This unit is motor-driven and controlled by a timing device. In normal operating schedules, the ovens are generally reversed every  $\frac{1}{2}$  hr.

**Regulation of oven heating** is of utmost importance and requires coordination of three elements: gas supply, draft, and air supply. Gas pressure is regulated by automatic control, and the gas is now often heated by steam coils to give uniform temperature before it enters the distributing headers, thus avoiding condensation within the distribution system. Orifices provide further means of regulating gas flow to each oven and to each heating flue. Battery draft is regulated by a stack damper operating under automatic control. In addition, each oven (and in some cases each flue) is provided with an individual damper. Air flow is usually controlled individually for each oven by finger bars or dampers.

**Pointers for Efficient Oven Heating.** The following points are to be observed for efficiency in heating by-product coke ovens:

1. Fuel gas and air should be regulated to obtain complete combustion with a minimum of excess air.
2. Stack draft should be kept at a minimum so as to avoid drawing oven gases through the walls into the heating flues.

<sup>1</sup> Ess, T. J., *Iron Steel Engr.*, pp. C13-C18.

3. Gas-inlet nozzles should be kept clean.

4. Oven pressure should be regulated so as to avoid pulling flue gases through the walls into the ovens.

5. Heat distribution throughout the oven should be such that coking proceeds evenly in all parts of the oven. This requires proper regulation of heating to individual flues and ovens, as well as the elimination of leakage through the brickwork. Because of the taper of the oven, each foot of oven length from pusher side to coke side contains progressively more coal than the preceding foot and consequently requires more heat input if even coking is to be obtained. Also both ends of the oven require a greater input because of heat losses through doors.

6. Time between pushing and charging each oven must be a minimum. A regular pushing schedule should be followed. Some pushing schedules allow for periodic idle time on each oven so as to permit effective removal of carbon from walls, roofs, and standpipes.

7. Regularity in the quantity of coal charged is essential.

**Heat Required.** With full battery operation, 2 to 2½ million Btu are required to heat the ovens per ton of coal coked. This means 3,900 to 4,900 cu ft of coke-oven gas per ton of coal, or 37 to 48 per cent of the total gas produced. With decreased operations and longer coking time, the proportion of gas required for heating gradually increases until there is no surplus. Figure 6-4, based on actual practice, illustrates this.

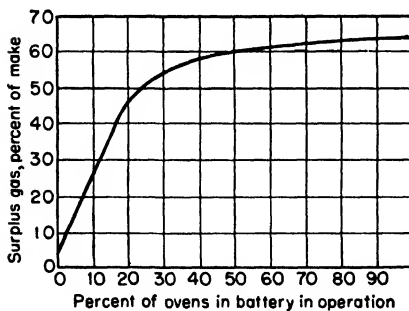


FIG. 6-4. Per cent ovens in operation vs. surplus gas. (*Ess, Iron and Steel Engineer*, 1948.)

than do richer gases. However, blast-furnace gas varies widely in quality and at times presents ignition difficulties. Also, if the blast-furnace gas drops below a calorific value of 95 Btu per cu ft, oven production will fall below rated capacity. To overcome these difficulties, blast-furnace fuel gas may be enriched by the addition of some coke-oven gas. In some cases, the two gases are mixed so as to give a resultant calorific value of 100 to 150 Btu per cu ft. The addition of coke-oven gas must be limited when the gas is put through regenerators. Otherwise methane in the coke gas is cracked, reducing heat value and forming carbon deposit. An increase of about 15

Table 6-5. Distribution of Heat Supplied to By-product Ovens<sup>1</sup>

	Btu/lb coal	Per cent
Sensible heat in dry flue gas. . .	154	12
Sensible and latent heat in water vapor in flue gas . . .	167	13
Sensible heat in coke . . . . .	473	37
Sensible heat in coke gas . . . .	167	13
Sensible and latent heat in tar and water vapor in coke gas . . .	154	12
Radiation and unaccounted for..	167	13
Total gross Btu supplied.....	1,282	100

<sup>1</sup>The Modern Coke Plant, *Iron Steel Engr.*, 1948.

#### Fuels Used for Coke Ovens.

Although most of the ovens in the United States are heated with coke-oven gas, some blast-furnace gas, producer gas, water gas, and refinery gas are also used. In the integrated steel plant, well-cleaned blast-furnace gas is well adapted to heating ovens designed for gas regeneration, thus releasing additional coke-oven gas for other heating operations in the steel plant. Blast-furnace gas for oven heating should be cleaned to a dust content not exceeding 0.005 grain per cu ft.

Lean heating gas tends to produce a more even heat in the combustion flues

Btu per cu ft in the mixed gas is perhaps the maximum enrichment when the gas is to be preheated. Many recent plants, however, are designing so that the enriching gas may be introduced directly into the heating flues, with independent regulation for each flue.

When ovens are heated with coke-oven gas, there is a tendency for carbon to form in underjet gas risers, gun flues, nozzles, and gas channels. This carbon is removed by passing air through these ducts during their off-gas period or during the reversal period. Air is supplied by natural draft or by a fan which runs continuously. When a fan is used, an 8- to 12-in. air duct runs the entire length of the battery, with 1½-in. branches leading to each reversing cock or to each gas flue. Ovens in which waste gases are recirculated seem to be relatively free of this carbon deposition, and decarbonizing apparatus is not normally installed with ovens of this design.

**Heating Large Ovens.** The trend toward larger ovens, with their greater capacities, introduced some heating problems which led to changes in the heating systems. The two major problems were the handling of the greater volume of gases needed for heat-

**Table 6-6. Temperatures Prevailing around By-product Coke-oven Battery<sup>1</sup>**

(In degrees Fahrenheit)	
Preheated air.....	1500-2100
Flame.....	2800
Oven flue.....	2200-2750
Oven wall.....	1900-2300
Oven top.....	1400-1500
Coke.....	1800-2000
Gas leaving oven.....	1100-1300
Gas entering collecting main.....	550-750
Gas entering suction main.....	75-275
Liquor in collecting main.....	175 or less
Oven stack.....	550-650

<sup>1</sup>The Modern Coke Plant, *Iron Steel Engr.*, January, 1948, p. C16.

ing without too great a differential pressure, and the proper distribution of heat (particularly with rich heating gas) so as to coke the coal uniformly. The first problem has resulted in the division of the heating system into smaller units; the second has been solved by dilution of the rich heating gas with waste gas to give greater flame length, or by the use of high and low burners in alternate combustion flues. The recirculation of waste gases is effected by cross-connecting vertical fuel-gas risers so that the fuel gas, passing through an injector nozzle and aspirator throat, draws some of the waste gas from the exit side over into the stream of incoming fuel gas.

With **high and low burners**, the burners in alternate heating flues are placed 12 to 27 in. above the level of the oven floor, while in the intervening flues, the burners are 6 in. above floor level. This arrangement tends to distribute the high-temperature zone of initial combustion vertically when heating with rich gas.

**Placing New Ovens in Service.** New ovens must be carefully dried and heated to avoid uneven expansion and cracking. Fire (wood or gas) is first placed in the coking chambers, and the temperature is brought up to about 250°F over a period of 2 weeks or more, the fires being vented into the combustion chambers through temporary holes in the oven walls. Coal or gas fires are then used, and the temperature is raised about 25°F each day for 4 or 5 weeks, after which the temperature can be brought up nearly to operating range. At this point, 3 or 4 days before charging, the gas is turned into the normal fuel-gas heating system. Tie rods and expansion joints must be carefully watched during the drying and heating process.

**By-product Battery Chimneys.** Waste gases leaving the regenerators pass through one or two waste-heat flues of about 50 sq ft cross section which run along one or both sides of the battery and are connected to the oven chimney. In some cases, two connections are used so as to provide better balanced draft. The oven chimney may be 225 to 275 ft high and 8 to 12 ft inside diameter at the top. It is usually constructed of radial brick. Automatically controlled regulating dampers in the flues leading to the stack maintain a constant draft upon the oven-heating system.

**Heat Balance of By-product Oven.** Table 6-7 gives a typical by-product oven heat balance. This heat balance gives no consideration to reactions occurring during the

Table 6-7. Typical Heat Balance of By-product Coke Ovens<sup>1</sup>

	Btu/lb coal	Per cent
Input:		
1. Latent.....	13,500	91 17
2. Sensible heat in coal ..	12	0 08
3. Latent heat in fuel gas ..	1,270	8 87
4. Sensible heat in fuel gas ..	12	0 08
Total input .....	14,794	100 00
Output:		
5. Latent heat in coke .....	9,563	64 62
6. Sensible heat in coke .....	520	3 52
7. Latent heat in gas ..	3,045	20 60
8. Sensible heat in gas ..	191	1 29
9. Heat of water vapor in gas .....	129	0 87
10. Latent heat of tar ..	598	4 04
11. Sensible heat of tar ..	6	0 04
12. Latent heat of light oils ..	132	0 89
13. Heat content in stack gas ..	440	2 98
14. Radiation and unaccounted for <sup>a</sup> ..	170	1 15
Total output .....	14,794	100 00

## Data for computation of Table 6-7

## Input:

- Gross heating value of 1 lb of coal as charged.
- Sensible heat in coal is so slight as to be negligible.
- Latent heat of fuel gas = cu ft supplied per lb of coal  $\times$  its gross calorific value per cu ft.
- Sensible heat in fuel gas = cu ft supplied per lb of coal  $\times$  temp of gas, deg F,  $\times$  volumetric heat content (approx  $0.0194 \times 0.0000047t$ , deg F for coke-oven gas).

## Output (equals input):

- Gross heat value of coke produced from 1 lb of coal.
- Sensible heat in coke = lb of coke produced from 1 lb of coal  $\times$  coke temp  $\times$  mean specific heat (approx 0.36).
- Latent heat in gas = cu ft of gas from 1 lb of coal  $\times$  gross heating value per cu ft.
- Sensible heat in gas = cu ft of gas from 1 lb of coal  $\times$  outlet-gas temp  $\times$  specific heat (as in item 6).
- Heat content of water vapor in gas = lb of moisture carried from gas by 1 lb of coal  $\times$  (1,090.7 +  $0.46 \times$  outlet-gas temp).
- Latent heat in tar = lb of tar from 1 lb of coal  $\times$  gross heating value per lb (approx 16,500 Btu per lb).
- Sensible heat in tar = lb of tar from 1 lb of coal  $\times$  temp, deg F,  $\times$  specific heat (approx 0.5).
- Latent heat in light oils = gal produced from 1 lb of coal  $\times$  gross heating value (approx 150,000 Btu per gal).
- Total stack loss = (lb of waste gas per lb of coal coked)  $\times$  (stack temperature)  $\times$  (mean specific heat) (approx 0.24) - (lb of moisture in stack gas)  $\times$  (1,090.7 +  $0.46 \times$  stack temp, deg F).
- Radiation, etc., is found by difference. The loss through walls, etc., has been estimated at an average of 195,000 to 200,000 Btu per oven per hr. A breakdown of this loss is somewhat as shown in Table 6-8.

<sup>1</sup> The Modern Coke Plant, *Iron Steel Engr.*, 1948.<sup>a</sup> See Table 6-8 for further breakdown of radiation loss.Table 6-8. Heat Loss by Radiation from By-product Coke Oven<sup>1</sup>  
(Estimated)

Area	Heat Loss, Btu/Sq Ft/Hr
Doors and frames .....	600- 900
Charging lids and frames .....	2,500-4,000
Oven tops ..	150- 300
Tops of heating flues.....	280- 590
Leveling door .....	800-1,500
Gas-collection piping.....	150- 225
Regenerator walls .....	100- 200
Lower oven structure.....	60- 80
Regenerator bottoms.....	130- 160
Total .....	4,770-7,955

<sup>1</sup> The Modern Coke Oven, *Iron Steel Engr.*

Table 6-9. By-product Coke Plant Operating Performance<sup>1</sup>

	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Plant G	Avg
Analysis of coal:								
Volatile matter, per cent	33 60	31 10	32 50	28 30	28 50	30 80	30 30	30 73
Fixed carbon, per cent	57 17	61 40	62 10					60 22
Moisture, per cent	2 75	2 68	4 00	4 90	6 30	6 60	3 80	4 43
Ash, per cent	9 25	7 44	5 40	7 80	7 50	6 90	6 50	7 26
Sulphur, per cent.	1 01	0 87	0 78	0.85	0 84	1 06	0 82	0 89
Analysis of coke:								
Volatile matter, per cent	0 67	1 01	0 80	1.10	1 40	1.40	1 60	1 14
Fixed carbon, per cent	87.85	89 20	92 70					89 92
Ash, per cent	11 79	9 80	6 50	9 30	9 50	9 30	9 00	9 31
Sulphur, per cent	0 72	0 71	0 61	0 63	0 83	0 83	0 65	0 71
Moisture, per cent	1 11	1 78	3 00	3 30	6 30	1 00	0 50	2 43
Oven width, in. (avg)	14	14	17	16.50	17 25	17	17 25	16 14
Gross coking time, hr and min.	11:46	13:04						12 25
Net coking time, hr and min	11:26	12:30	17:00	16:20	15:08	15:08	17:05	14 57
Coal charged per oven, net tons		12 50	18 00	13 25	17.00	17 41	18 02	16 03
Total coke yield, per cent	75 75	76 00	74 10	77 70	73 70	77.69	79 00	76 28
Furnace coke yield, per cent	63 07	61 00	65 00					63 02
Domestic coke yield, per cent	6 98	10 00	3 70					6 89
Pea coke yield, per cent	0 00	0 50	1 50					0 67
Breeze yield, per cent	5 70	4 50	3 90	6 00	4 20	7 22	8 00	5 65
Tar, gal/ton coal	11 03	11 30	8.85	6 70	6 20	6 96	8 80	8 55
Ammonium sulphate, lb/ton coal	25 21	25.50		18.10	19 90	15 94	21 60	21 04
Light oil, gal/ton coal	3 60	3 40	3 25	2 90	2 90			3 21
Ammonia liquor, gal/ton coal		14 00						
Total gas, cu ft/ton coal	10,130	10,200	10,200	10,353	10,234	10,719	12,053	10,556
Gas to heat ovens, cu ft/ton coal		3,900		4,356	4,465			4,240
Surplus gas, cu ft/ton coal		6,300		5,997	5,769			6,022
Surplus gas, per cent of total		61 8		58 0	57 3			59 0

<sup>1</sup> The Modern Coke Plant, *Iron Steel Engr.*, January, 1948, p. C29.Table 6-10. By-product Coke, Analyses of Typical Field Samples<sup>a</sup>

Where purchased	Ash, per cent	Volatile, per cent	Moisture, per cent <sup>b</sup>	Fusion, deg F <sup>c</sup>	Heat value, Btu	
					Dry	Apparently dry <sup>b</sup>
Norristown, Pa	10 60	1 36	7 6	2379	12,804	11,850
Philadelphia	7 61	1 00	10 8	2534	13,234	11,800
Chester, Pa	7 93	2 25	10 5	2630	13,289	11,890
Camden, N.J.	7 12	1 75	10 3	2386	13,286	11,900
	8 54	2 05	11 7	2200	13,053	11,520
Newark, N.J.	5 57	0 85	7 1	2563	13,512	12,550
Brooklyn, N.Y.	0 12	1 53	9 6	2427	13,476	12,170
	5 67	0 61	8.7	2534	13,502	12,310
Lowell, Mass	6 51	1 89	11.5	2503	13,414	11,880
Lawrence, Mass	4 55	1 68	14.6	2099	13,695	11,690
Hartford, Conn	6 84	0 91	11 6	2548	13,313	11,790
Providence, R.I	6 66	1 36	8 3	2720	13,400	12,280
Boston, Mass	7 96	0 76	8 4	2591	13,165	12,070
Alabama	7 39	1 01	8 8	2548	13,365	12,190
Troy, N.Y.	9 11	0 84	9 2	2705	13,013	11,820
Buffalo, N.Y.	8 98	1 95	8 9	2705	12,983	11,820
Utica, N.Y.	9 19	0 86	11 5	2534	13,010	11,520
Syracuse, N.Y.	9 51	0 82	12 5	2734	12,950	11,320
Fairmont, W.Va.	8 52	1 94	9.5	2284	13,121	11,880
Hamilton, Ont	9 46	1 60	11.6	2591	13,033	11,510
Montreal, Que.	7 44	0 62	7 6	2456	13,235	12,210
Avg.	7 68	1.32	10.0	2508	13,231	11,856

<sup>a</sup> Samples purchased from retail outlets.<sup>b</sup> Measured at a point when the surface appeared dry.

Table 6-11. Yield and Analyses of Products of Carbonization Process<sup>1</sup>

Product and constituents	Per cent of coal by weight	Per cent of product by weight	Yield, lb/ton coal
Coke:			
Ash . . . . .	7 210	10.24	144 20
Carbon . . . . .	61 711	87 76	1234 22
Hydrogen . . . . .	0 469	0 66	9 38
Sulphur . . . . .	0 683	0 96	13 66
Nitrogen . . . . .	0 270	0 38	5 40
Totals..	70 343	100 00	1406 86
Gas:			
Carbon dioxide . . . . .	1.042	6 66	20 84
Carbon monoxide . . . . .	3 154	20 14	63 08
Methane . . . . .	7 468	47 69	149 36
Ethylene . . . . .	1 529	9 76	30 58
Nitrogen . . . . .	0 385	2 46	7 70
Hydrogen . . . . .	1 366	8 72	27 32
Oxygen . . . . .	0 717	4 57	14 34
Totals	15 661	100.00	313 22
Ammonia:			
Hydrogen . . . . .	0 040	17 90	0 80
Nitrogen . . . . .	0 183	82 10	3 66
Totals	0 223	100 00	4 46
Tar:			
Carbon . . . . .	4 687	86 00	93 74
Hydrogen . . . . .	0 327	6 00	6 54
Oxygen . . . . .	0 436	8 00	8 72
Totals	5 450	100 00	109 00
Liquor:			
Moisture . . . . .	3 310	48 70	66 20
Oxygen . . . . .	3 107	45 60	62 14
Hydrogen . . . . .	0 388	5 70	7 76
Totals	6 805	100 00	136 10
Light oils, benzene (C <sub>6</sub> H <sub>6</sub> ) (equivalent)	1 102	100 00	22 04
Cyanogen, C <sub>2</sub> N <sub>2</sub> . . . . .	0 078	100 00	1 66
Carbon disulphide, CS <sub>2</sub> . . . . .	0 013	100 00	0 26
Hydrogen sulphide, H <sub>2</sub> S . . . . .	0 325	100.00	6.50

<sup>1</sup> The Modern Coke Plant, *Iron Steel Engr.*Table 6-12. Specific Heat of By-product Coke<sup>1</sup>

Temp, deg F	Mean specific heat, Btu/lb/deg F				
	Ash	Coke with ash content, per cent, of			
		5	10	15	20
400	0 204	0 225	0 224	0 223	0 222
750	0 227	0 277	0 275	0 272	0 269
1100	0 242	0 313	0 309	0 306	0 302
1500	0 250	0 337	0 333	0 328	0 324
1800	0 256	0.356	0.351	0 345	0 340
2000	0 258	0.363	0.359	0.353	0.348

<sup>1</sup> *Iron Steel Engr.*

coking stage of the process. These are generally recognized as exothermic. The omission of this item on the input side will have the effect of decreasing the output item of radiation and unaccounted loss. It is also apparent that the first stage of the process, including driving off of hygroscopic water and raising coal temperature to its fusion point (about 780°F), requires much more external heat than the subsequent coking stage.

#### Coal-gas-retort Coke<sup>1</sup>

Although the by-product and beehive ovens are the only forms of carbonization equipment which will produce satisfactorily metallurgical coke, several other types

**Table 6-13. Effect of Steaming Coal in Vertical Retorts<sup>1</sup>**

Ratio steam to coal carbureted, per cent	Blue gas, total per cent	Gas/lb of coal, cu ft	Btu/cu ft of gas	Btu in gas /lb of coal	Fuel, lb/ton of coal	Net coke and breeze, lb/ton of coal	Sp gr of gas
0	0 0	5 75	570	3,280	260	1,120	0 430
10	11 0	6.40	540	3,460	275	1,100	0 446
15	23 3	7 50	510	3,820	300	1,060	0 462
20	32 0	8 40	475	3,990	325	975	0 479
30	45 0	10 50	440	4,620	360	860	0 495

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 850, McGraw-Hill Book Company, Inc., New York, 1941.

**Table 6-14. Salient Statistics of the Coal-gas Industry in 1947<sup>1</sup>**

	Horizontal retorts	Vertical retort and gas oven	Totals and averages
Retorts in existence, Dec. 31, 1947	1,007	412	1,419
Retorts in operation, Dec. 31, 1947	755	399	1 154
Coal charged, net tons . . . . .	382,881	711,939	1,094,820
Coke produced, net tons . . . . .	234,965	429,611	664,576
Screenings or breeze produced . . . . .	19,720	57,604	77,324
Average yield in per cent coal charged:			
Coke . . . . .	61 37	60 34	60 70
Breeze (at plants recovering) . . . . .	8 24	8 67	8 56
Coke used by producer:			
For manufacture of water gas . . . . .	73,769	96,445	170,214
For manufacture of producer gas . . . . .		29,150	29,150
For bench fuel . . . . .	57,492	81,683	139,175
For other purposes . . . . .	9,222	6,705	15,927
Total used by producer . . . . .	140,483	213,983	354,466
Coke sold to other consumers:			
For manufacture of water gas . . . . .	10,021	3,255	13,276
For other industrial uses . . . . .	126	9,886	10,012
For domestic use . . . . .	88,403	194,263	282,666
Total sold . . . . .	98,550	207,404	305,954
Per cent of coke for domestic use . . . . .	37 6	45 2	42 5
Tar produced, gal/ton of coal . . . . .	11.80	14 72	13 70
Ammonia liquor, lb/ton of coal . . . . .		3 04	3 04
Crude light oil, gal/ton of coal . . . . .	0.20	1.18	0 91

<sup>1</sup> U.S. Bureau of Mines, ms. 1594.

of apparatus, such as the vertical and horizontal coal-gas retorts, become available when the production of gas is the prime consideration. In the manufactured-gas

<sup>1</sup> See also Coal Gas, p. 303.

industry, a gas meeting strict legal requirements must be made at all times, and the quality of coke and by-products may thus fluctuate to a certain extent.<sup>1</sup>

Usually about 50 per cent of the coke so produced is used by its producers for heating benches, for manufacturing producer gas and water gas, and for other miscellaneous plant uses; the bulk of the remainder is sold for household heating near the sources of production.

During recent years, coal-gas retorts have been rapidly replaced by other equipment such as that for water gas, natural gas, and liquefied petroleum gas. This steady recession of plants operating coal-gas retorts has markedly reduced the coal-carbonizing capacity of the industry so that, as of Dec. 31, 1947, some 1,419 retorts in existence were capable of carbonizing 1,273,100 net tons of coal a year, a decrease of 21 per cent from 1946 and of 33 per cent from 1942, the first year of record.<sup>2</sup>

### Blast-furnace Coke<sup>3</sup>

In the steel industry, the primary purpose of the coke plant is, of course, to produce coke for the blast furnaces. The by-products, however, are of such value as to offset the cost of coking.

Coke for the blast furnace must have definite physical and chemical properties which determine whether or not it will work satisfactorily in the furnace. Actually, blast furnaces operate successfully with cokes ranging from 6 to 14 per cent ash and 0.5 to 1.8 per cent sulphur, with porosity of 40 to 60 per cent, a 2-in. shatter index of 10 to 75 per cent, and a wide range of specific reaction rates and of mean size charged. Such variations stem from the dependence of these properties upon the coal that is available at a cost conducive to economical operation, and to a lesser extent upon coking practice.

However, while coke of such widely varying characteristics is used satisfactorily among the various blast furnaces, the coke going to an individual furnace must be uniform in physical structure, size, strength, and chemical composition if good operation is to be expected. Adjustments can be made to accommodate a coke of poor but uniform quality, but a smooth operation cannot result with a coke of good but varying quality.

Good furnace coke should resist abrasion and must not break up in the furnace. It should be hard but not brittle. Open cell structure in the coke favors rapid combustion, while a dense structure retards combustion.

In spite of much work to develop suitable coke tests, it is still impossible to predict accurately, from laboratory tests, the behavior of coke in the blast furnace. Coke that works satisfactorily in one plant may be quite unsuitable in another, and two furnaces in the same plant may work quite differently on the same coke. The real answer is to be had only from actual use in the blast furnace.

### Low-temperature Carbonization (Disco)<sup>4</sup>

The outstanding low-temperature carbonization operation in the United States is the McDonald, Pa (19 miles west of Pittsburgh), plant of The Disco Co., a subsidiary of the Pittsburgh-Consolidation Coal Co.

High-volatile coking coal, mainly from the Westland and Montour No. 4 deep mines, sized to  $-3/8$  in., is dried and fed to rotary kilns or carbonizers some 126 ft

<sup>1</sup> HASLAM, ROBERT T., and ROBERT P. RUSSELL, "Fuels and Their Combustion, p." 669, McGraw-Hill Book Company, Inc., New York, 1925.

<sup>2</sup> "Production of Coke from Coal-gas Retorts in 1947," Mineral Industries Surveys, U.S. Bureau of Mines, ms. 1594, 1948.

<sup>3</sup> Ess, T. J., *Iron Steel Engr.*

<sup>4</sup> *Utilization*, May, 1949.



long by 9 ft in diameter. The entering temperature of the coal charge is about 600°F; the exit temperature of the charge 850 to 900°F. Under the influence of the temperature (above about 700°F) the coal gives off hydrocarbon vapors and softens to form balls of various sizes. The plastic stage is of short duration, lasting only 5 or 10 min. The hot product, or "Disco," is sized and quenched, with the smaller fines being returned to the kiln to form part of subsequent charges.

Two sizes are marketed, 2 by  $\frac{3}{4}$  in. and +2 in. The ratio of the sizes produced is about 1 carload of the smaller to 7 of the larger. Volatile in the finished product averages about 16 per cent (from high-volatile coal). By-products consist of 15 gal of high-acid tar and 3,700 cu ft of 375-Btu gas. The tar is sold without further separation, the gas reused in the process to furnish heat. Gas is said to analyze 4.0 per cent  $\text{CO}_2$ , 10.0 per cent CO, 29.5 per cent  $\text{CH}_4$  (methane), 4.5 per cent illuminants, 49.9 per cent nitrogen, oxygen, hydrogen, hydrogen sulphide, etc. The gas contains light oils, which are not separated at present. The tar does not contain ammonia, being acidic rather than alkaline. Each carbonizer, of which there are now 9, has an hourly capacity of  $6\frac{1}{4}$  tons for a total daily input of 1,050 tons, with 72 to 75 per cent converted to Disco.

### SELECTION OF COALS FOR COKING<sup>1</sup>

Approximately 16 per cent of the bituminous coal in the United States is converted into coke. In the early days of the coke industry, high-grade coking coals were plentiful, but reserves of these coals are gradually giving out, with the result that the less desirable grades must be used. Sulphur and ash contents have gradually increased through recent years, and there is much activity to find and develop new coals suitable for coking. The blending of two or more coals has made enormous coal reserves available for coking.

**Sources of Coking Coal.**<sup>2</sup> According to the U.S. Bureau of Mines<sup>2</sup> the great source of coking coal has been the Appalachian region, extending from Pennsylvania to Alabama. States in this region supplied more than 96 per cent of all coal purchased in 1946 for oven coke. In order of tonnages, the ranking states which shipped coal to oven-coke plants were Pennsylvania and West Virginia, each furnishing 36 per cent of the total; Kentucky 14 per cent; Alabama 8 per cent; and Virginia and Tennessee combined 2 per cent. Other states that supplied significant tonnages of coking coal were Utah and Colorado, which together furnished 2 per cent of the total. The best high-, medium-, and low-volatile coking coals are found in West Virginia, eastern Kentucky, western Virginia, Pennsylvania, and Alabama. The low-volatile coking coals, such as are very important for improving the physical properties of metallurgical coke, especially its strength, come mostly from West Virginia and, to a lesser extent, from central Pennsylvania, western Virginia, Oklahoma, and Arkansas.

The expansion of the steel industry in the Far West during the Second World War focused attention on the supply of coking coal from that area. The present source of coking coal for the steel plants in Utah and California is the Sunnyside bed of Utah. Through exploration, the U.S. Bureau of Mines has discovered additional reserves of coking coal near Kemmerer, in southwestern Wyoming, and in Gunnison County, Colorado.

Coke-plant operators reported to the Bureau of Mines that 59 per cent of all coal purchased for the manufacture of oven coke in 1946 was obtained from captive mines.

**Effect of Coal Properties on Coking.**<sup>3</sup> The suitability of a coal for producing coke

<sup>1</sup> Ess, T. J., *Iron Steel Engr.*, pp. C5-C7.

<sup>2</sup> "Minerals Yearbook," U.S. Bureau of Mines (available through Superintendent of Documents), preprint p. 24, 1946.

<sup>3</sup> Ess, T. J., *Iron Steel Engr.* See also *The Practical Effect of Various Properties of Coal*, p. 36.

depends upon many properties and characteristics, several of which are very difficult to evaluate without actual trial in an oven. Volatile matter, ash, and sulphur content are among these many factors of primary importance.

**Volatile Content.** Coals of very high volatile content result in coke of relatively low strength, and they are thus usually used in a blend with low-volatile coals. Low-volatile coals have a tendency to expand when heated and yield somewhat lower quantities of coal chemicals or by-products.

Volatile matter should fall between 28 and 35 per cent in coal on a dry ash-free basis. Coals of higher volatile content are often used but at the expense of the strength of the coke.

**Ash.** Ash in the coal is of course carried over into the coke. Ash content of coke is about 1.35 times that of the coal charged to the oven. High-ash coal is said to reduce iron production by about 5 per cent for each per cent of ash.

Low ash is desirable, the lower the better, and with not over 10 per cent if at all possible.

**Sulphur.** Between 60 and 70 per cent (usually 62 per cent) of the sulphur in the coal remains in the coke. It should therefore be as low as possible, preferably not over 1.2 per cent for coke for blast-furnace use, and 1.0 per cent for coke for foundry use.

**Moisture.** Excessive moisture in the coal may injure the oven brickwork. Seven per cent may be considered a maximum.

**Oxygen Content.** Coke of best quality is made from coals of relatively low oxygen content. More than 8 per cent oxygen on a dry ash-free basis will not make good commercial coke, although higher oxygen coal is used in some cases. Some authorities state that a hydrogen-oxygen ratio of 0.6 or more is desirable, with 0.55 a minimum value.

**Expansion on Heating.** During the coking process, coals may undergo marked changes in volume. Some coals may expand while others contract, and there is no sure way to predict exactly which way a coal will behave except by actual test.

In general, low-volatile coals expand and high-volatile coals contract, even though the coals come from the same seam. Tests of coals from the lower Kittanning seam show 40 per cent or more expansion with 17 to 18 per cent volatile matter, and 27 to 30 per cent contraction with 42 per cent volatile. At approximately 31 per cent volatile, there seems to be no volume change. Similar tests on No. 3 Pocahontas seam shows 20 per cent expansion with 17 per cent volatile matter and 3 per cent expansion with 24 per cent volatile. (All volatile contents in these tests are reported on the dry ash-free basis.)

Since expanding coals may exert dangerous pressures against the oven walls, it is necessary that such coals be used in blends with coals that contract while coking so that the final mixture is approximately neutral. Even then care must be exercised not to vary coking practice, as mixtures which may be safe when coked for long times at low temperatures may be dangerous at faster coking rates with higher temperatures. Likewise, the expansion of a coal or a coal mixture will increase if the bulk density of the charge increases. Finer pulverization and increased moisture (up to

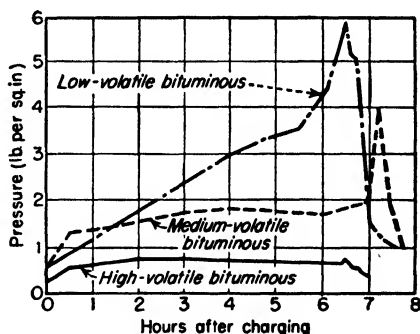


FIG. 6-5. Pressures developed by three typical coals during coking process. (*Eas, Iron and Steel Engineer, 1948.*)

7 per cent) tend to reduce density and hence reduce expansion during coking. See also Plastic Properties of Bituminous Coals, page 93.

**Pressures Developed by Coals.** According to Ess,<sup>1</sup> pressures developed by bituminous coals may range somewhat as follows:

**High-volatile Bituminous.** From  $\frac{1}{2}$  to  $\frac{2}{3}$  psi, remaining more or less constant through the coking process.

**Medium-volatile Bituminous.** From  $\frac{1}{2}$  psi at charging to  $1\frac{3}{4}$  psi after  $\frac{1}{2}$  hr, and then remaining rather constant except for a sudden peak of 4 psi at 7 hr.

**Low-volatile Bituminous.** From  $\frac{1}{2}$  psi at charging up to 6 psi at  $6\frac{1}{2}$  hr. The occurrence of pressure peaks in an otherwise uniform pressure record shows that ovens may be damaged, even though badly sticking ovens are not encountered in pushing.

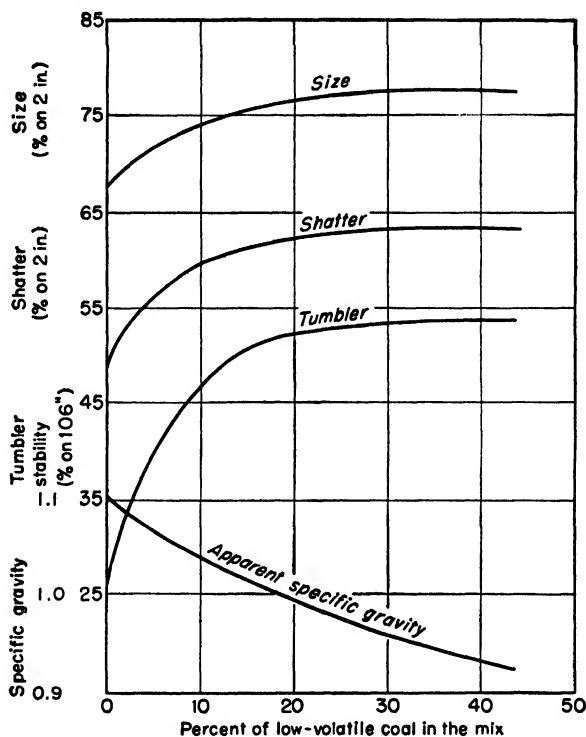


FIG. 6-6. Variations in physical properties of coke with varying proportions of low-volatile coal in the mix. (Ess, *Iron and Steel Engineer*, 1948.)

These pressure characteristics of the several very general types of coal are also shown as Fig. 6-9.

**Size Consist.** The sizing of the raw coal affects coke quality to a considerable extent. Harder coke is obtained from pulverization to 70 per cent through  $\frac{1}{8}$ -in. mesh than if pulverized to 50 per cent through  $\frac{1}{8}$ -in. There is considerable variation in the degree of pulverization through the industry, depending principally on local conditions and the use for which the coke is primarily intended. In general, operators seem to favor pulverization so that 80 to 90 per cent passes through  $\frac{1}{8}$ -in.-mesh screen, particularly if the blending of two or more coals is being employed. A high degree of pulverization results in less segregation and a more intimate mixture,

<sup>1</sup> Ess, T. J., *Iron Steel Engr.*

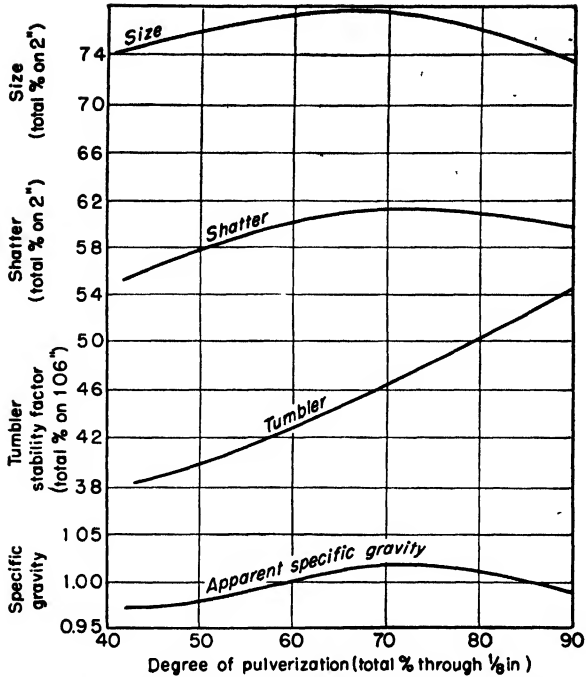


FIG. 6-7. Effect of degree of pulverization of coal on physical properties of resultant coke. (*Ess, Iron and Steel Engineer*, 1948.)

although it also gives lower bulk density, and, if the mixture contains too much very fine coal, coke quality suffers. Some operators believe that fine crushing of the coal results in higher coal-chemical (by-product) yield. In some cases, where only high-

Table 6-15. Typical Analyses of By-product Coke from Various Coals<sup>1</sup>

Kind of coal	Per cent by weight									
	Water	Volatile	Fixed C	Ash	S	P	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Bases	Fe
Connellsville, Pa . . .	0 32	1 70	86 50	11 50	0 75	0 020	5 30	3 00	4 30	2 60
Pocahontas, W. Va . .	.	2 31	90 62	6 97	0 70					
New River, W. Va . .	.	2 82	90 52	6 36	0 70					
Davis, W. Va . . . . .	0 33	1 20	87 97	10 50	0 55	0 034	4 27	3 89		1 40
Derry, Pa . . . . .	.	2 50	81 60	14 70	1 20					
Webster, Pa . . . . .	.	1 10	88 40	10 50	0 95	0 030	4 80	3 50		1 85
Klondike, Pa . . . . .	.	2 50	84 50	12 00	1 00					
Loyalhanna, Pa . . . .	.	2 45	81 20	15 00	1 35					
Mountain, Pa . . . . .	0 50	1 10	85 85	11 53	1 00	0 018				
Fairmont, W. Va . . . .	0 30	0 97	87 43	11 30	1 35	0 020	4 16	2 53		2 45

<sup>1</sup> *Iron Steel Engr.*

volatile coals are used, and even where mixtures of coal are used, coarse coal (up to 1½ in.) is used to obtain high bulk density. The best size of pulverized coal must be determined by the individual plants for each coal or blend used.

**Bulk Density.** Control of bulk density of the coal charged to the ovens has recently received considerable attention. Such control results in coke with more uniform physical characteristics and also simplifies heating and operation of the ovens. The principal factor affecting bulk density is the surface moisture of the coal, although fineness of crushing is also important. Bulk density decreases as surface moisture increases and as coal fineness increases. The effect of moisture content can be offset to a great extent by the addition of small amounts of oil to the coal charge. Such additions increase the bulk density of wet coal but may reduce somewhat the bulk density of coal that has no surface moisture. Results from tests in one plant showed that the addition of 1 gal of oil per ton of coal resulted in a 7 per cent increase in bulk density and that the use of oil decreased the fluctuations in density caused by changes in moisture content of coal.

#### Coke Yield as Affected by Coal Properties<sup>1</sup>

Coke yields as obtained from various coals are closely proportionate to the rank of the coal as measured by its fixed carbon, running 102 to 113 per cent of the fixed carbon plus ash content of the coal as carbonized. The coke yield is greater than the fixed carbon plus ash contents because of the deposition of carbon by thermal decomposition of hydrocarbons in gases and vapors passing through the coke mass. When coke yields (dry) are plotted against fixed carbon plus ash, a straight line develops, the formula being

$$\text{Per cent coke yield, dry} = 19 + 0.79(C + A)$$

where  $C$  = per cent of fixed carbon in the coal

$A$  = per cent of ash in the coal

The ash content of the coke, which equals the ash content of the coal divided by the coke yield, may therefore be expressed as

$$\text{Per cent of ash in dry coke} = \frac{100A}{19 + 0.79(C + A)}$$

with symbols as in the preceding equation.

Coke yield drops as the carbonizing temperature is increased up to about 1650°F, because of the more complete driving off of the volatile matter, which reaches a minimum of about one-half at this temperature. The carbon content of the coke increases, and the Btu per pound of coke decreases simultaneously. Above 1650°F, the coke yield increases slightly because of carbon deposition.

#### Relation of Coke Characteristics to Rank of Coal

According to Perch and Russell,<sup>2</sup> there is sufficient evidence from past experience to indicate that characteristics of coke produced from a given coal are in some measure related to the rank of coal. Broadly speaking, the high-volatile C bituminous coals make very small fragile cokes, if the coals coke at all; whereas the high-volatile A coals produce much better cokes. Although the low-volatile coals produce strong cokes, they cannot be carbonized unblended in by-product ovens because of their pressure characteristics.

After a careful effort to use some interpretation of the standard method of classifying coal as a prediction of the coking properties, the authors concluded that a modification was necessary to express results properly. They thus devised a chart in which

<sup>1</sup> Ess, T. J., *Iron Steel Engr.* pp. C30, C31.

<sup>2</sup> PERCH, MICHAEL, and CHARLES C. RUSSELL, A Study of Coal Classification and Its Application to the Coking Properties of Coal, *Mining Eng., AIME*, June 1949, p. 205.

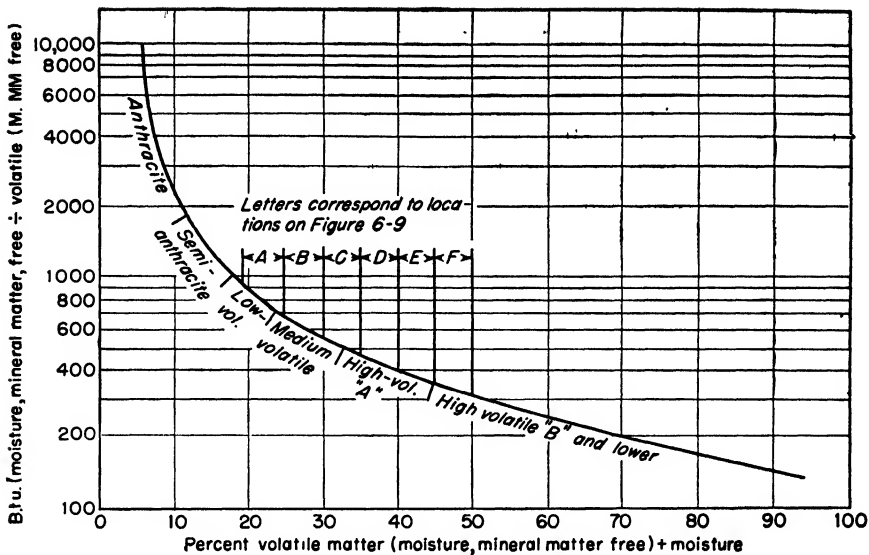


FIG. 6-8. Classification chart of coals showing the relation of coking properties to chart location. (Based upon Perch and Russell, *Mining Engineering*, June, 1949.)

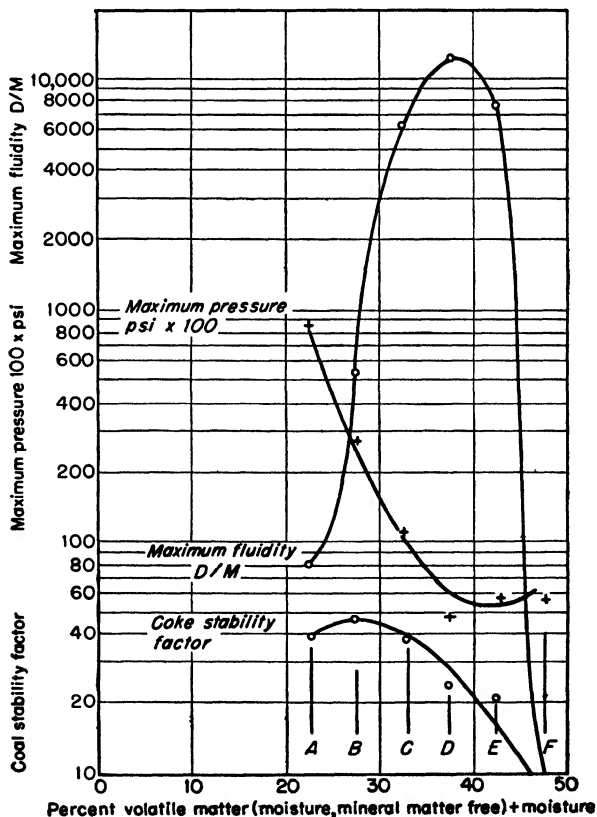


FIG. 6-9. Relation between coking properties of coals and volatile +  $H_2O$ .

the ratio of the heating value of the coal to percentage of volatile matter is plotted as the ordinate on a logarithmic scale and dry volatile matter plus moisture is plotted as the abscissa on an arithmetic scale. Both are on a mineral-matter-free basis. In the resultant chart, all ranks of coal (except anthracite) fell practically on the curve.

A general examination of this classification scheme revealed that the coals appeared to be aligned in order of their determined coking behavior. Figure 6-8 shows this curve, on which are also shown the *very approximate* divisions between the major ranks of coal.

Superimposing some 36 coals of known coking behavior on this modified classification curve, the authors found that all fell within the range marked *A* to *F* on Fig. 6-8. A further analysis of this imposition shows that, for each segment of the curve, marked *A* to *F*, plottable points are available for pressure, fluidity, and stability. These are shown as Fig. 6-9. While the authors referred to the curve for a location of individual coals, if all points fall on the curve as stated, only the abscissa, or per cent volatile moisture, as used in Fig. 6-8, is needed to establish a relationship between coal characteristics and coking properties. (It should be noted that this is a very new, relatively unproved relationship. However, in view of the paucity of technical guides as to the suitability of coals for coking, it is presented with this reservation, and with considerable modification by the editors.)

Table 6-16. Relation between Volatile + Moisture, and Coking Characteristics<sup>1</sup>

Location on Figs. 6-8 and 6-9	Volatile + moisture*	No. of analyses	Max fluidity, <i>D/M</i>	Max pressure, psi	Coke stability factor	Per cent ash in coal
<i>A</i>	19-25	6	76	8 06	40	4 7-13
<i>B</i>	25-30	2	530	2 57	48	5 1-18
<i>C</i>	30-35	5	6,370	1.07	39	3 6-26
<i>D</i>	35-40	7	11,570	0 48	24	4 7-7 7
<i>E</i>	40-45	9	7,335	0 59	22	3 5-15
<i>F</i>	45-50	7	7	0 58	6	3 1-20

<sup>1</sup> PERCH, MICHAEL, and CHARLES C. RUSSELL, *Mining Eng., AIME*, June, 1949, p. 205.

\* Volatile is moisture- and mineral-matter-free. See Figs. 6-8 and 6-9 for graphic presentation of this material.

### BLENDING COALS FOR COKING<sup>1</sup>

In 1946, 72 of the 85 active plants in the United States carbonized coal of different volatile content. High- and low-volatile coals were blended by 46 plants; high-, medium-, and low-volatile by 3 plants; and high- and medium-volatile by 3 plants. Of the plants that carbonized straight or unblended coals, 10 used straight high-volatile and 3 medium-volatile. At plants where blending is practiced, the proportion of the different kinds of coal mixed before charging into ovens varies widely from plant to plant according to local conditions. A classification of all coal purchased for coking in vertical slot-type ovens in 1946 indicated, however, that 66 per cent was high-volatile, 13 per cent medium-volatile, and 21 per cent low-volatile.

While exact performance depends upon local conditions, on a basis of tests in which 100-lb samples were carbonized in a horizontal steel retort, Mendelshon<sup>2</sup> reports that the yield resulting from the blending of bituminous coals may be predicted from the following equation:

$$\text{Per cent coke yield} = \frac{1}{100}[ax + (100a)y]$$

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, preprint 1946, p. 24.

<sup>2</sup> MENDELSHON, J., *Fuel*, vol. 13, No. 5, pp. 140-154, 1934, as quoted by *Penn. State Coll. Mineral Inds. Expt. Sta. Cir.* 16, p. 10.

where  $a$  = per cent of one coal in the blend

$x$  = per cent of coke produced from this coal

$y$  = per cent of coke produced from the other coal

The agreement between this equation and actual test results published by the Bureau of Mines is said to be excellent.

### Anthracite Fines in Coke Production<sup>1</sup>

Since 1942, there has been a progressive increase in the use of anthracite fines in mixture with high- and low-volatile bituminous coals for feed stock in the production of blast-furnace and foundry coke. The material is considered an inert, which appears to permit the use of higher flue temperatures and shorter coking time and thus increases the throughput.

In general, the following characteristics are of importance in selecting anthracite fines for use in blends:

1. Particle size
2. Size consist (size distribution)
3. Density, volatile content, and sulphur
4. Ash content

No. 5 buckwheat anthracite specification is considered the best suited for blending use, although there is presently an interest in the flotation anthracite at some plants.

In general, the size consist most desired is

Mesh	Max Per Cent
10	5
10- 20	20
20- 40	60
40-100	10
100	5

Volatile-matter content is generally limited to 6 per cent maximum. True specific gravity is approximately 1.70 with 50 per cent sink in carbon tetrachloride. Low ash content.<sup>2</sup>

### Use of Anthracite Fines in By-product Coke Blends<sup>3</sup>

Clendenin, Barclay, and Wright report the technical aspects of blending anthracite fines with bituminous coals for making by-product coke in considerable detail, with emphasis on the several factors influencing the quality and yield of the products.

They conclude that, up to at least 10 per cent anthracite addition, the properties of the resultant coke appear to be entirely satisfactory for non-blast-furnace uses, such as for foundries, water-gas generators, and domestic fuel. On the other hand, cokes produced from blends containing small percentages of anthracite fines are not, as yet, generally acceptable for modern blast-furnace use. It is claimed by some operators that anthracite-blend cokes possess a deficiency in certain desirable strength characteristics which is reflected in a disturbance in the blast-furnace operating cycle. Recently, however, at least one blast furnace reported favorably on the use of 5 per cent anthracite in their coking blend, and several other plants are reported as trying the use of 2½ to 3 per cent blends. In the non-blast-furnace field, several different

<sup>1</sup> KERRICK, J. H., research engineer, The Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa.

<sup>2</sup> For further technical information, refer to *Penn. State Coll. Mineral Inds. Expt. Sta. Circ. 16 and Tech. Paper 136*.

<sup>3</sup> CLENDENIN, J. D., K. M. BARCLAY, and C. C. WRIGHT, The Technical and Economic Aspects of the Use of Anthracite Fines in By-product Coke Production, *Penn. State Coll. Bull., Mineral Indus. Expt. Sta. Circ. 16*, 1944.



plants are known to be using about 5 per cent No. 5 buckwheat anthracite in their coking blends, and a number of foundries are now operating on such cokes.

For carbonization in regular by-product ovens, the use of more than 20 per cent anthracite in the blend has not proved feasible for the production of coke. Additions of anthracite in excess of about 10 per cent affect the size distribution and physical properties of the coke adversely. Maximum upgrading in shatter index of the coke is reached at about 10 per cent anthracite, while the tumbler-test stability and hardness factors appear to show slight but progressive decreases with increasing additions of anthracite.

**Yield.** The use of several per cent of anthracite will permit a reduction in the coking time and consequently an increase in throughput, conservatively estimated to amount to at least 10 per cent. The increased throughput will vary with particular conditions, and there is no evidence to indicate that increasing the percentage of anthracite will permit further reductions in the coking time. Within the admixture range of 0 to 10 per cent anthracite, the yield of coke has been found to increase approximately 0.1 per cent for each per cent of anthracite added to the blend.

**Effect on Gas Yield.** The yield and heating value of the gas from the carbonization of anthracite is less than that from an equal weight of bituminous coal. For low- and medium-volatile anthracites the yield and thermal value of the gas may be expected to average about 5.3 million cu ft and 1.8 million Btu respectively, per ton of coal. Additions of anthracite to bituminous coal will therefore reduce both the yield and quality of the gas per unit weight of blend carbonized. The reduction in volume per unit weight of blend carbonized is about 0.5 per cent for each per cent of anthracite added, while the reduction in thermal value is about 0.6 to 0.7 per cent for each per cent of anthracite added. Because of the increased throughput, however, the use of anthracite permits an increase in the daily gas production. Calculated to an equivalent heating value, the increased daily gas production may reach as much as 5 to 6 per cent. Additions of anthracite greater than 11 per cent result in a decreased yield of gas on both the daily and the per ton of coal or coke basis.

**Effect on By-products.** Available data suggest that anthracite has no residual value for the production of by-products other than gas and may be considered as an inert diluent. The by-product yield per ton of blend carbonized is therefore inversely proportional to the percentage of anthracite used in the blend. As with gas yield, however, the increased throughput counteracts the decrease in unit weight, and increases in the daily by-product yield up to about 5 per cent should be possible with the smaller percentages of anthracite. Addition of anthracite in excess of 8 per cent will probably result in a decrease in daily yield as well as the yield per ton of coal or coke.

### Advantages and Disadvantages of Blending Anthracite<sup>1</sup>

Clendenin and Kohlberg list and discuss the following reasons for and against blending anthracite with bituminous coal for the manufacture of coke:

#### Reasons for Blending Anthracite

1. With proper blending, there is an increase in the percentage yield of foundry-sized coke.
2. Increased daily yield of foundry coke by use of higher flue temperatures and shorter coking times is feasible.
3. Small increase in percentage yield of total coke is noted.
4. Coke strength and hardness as measured by the shatter test are increased.

<sup>1</sup> CLENDENIN, J. D., and JOSEPH KOHLBERG, *The Blending of Anthracines in Coke Production*, Penn. State Coll. Tech. Paper 136, 1948.

5. Greater uniformity of coke size is obtained.
6. There is an additional source of available coal.
7. No additional pulverizing and screening equipment is needed.
8. Possibly, more rapid heat transfer in oven charge is induced.
9. Relief from excess oven pressure of low-volatile coals in mix can be secured by substitution of fine anthracite for part of the low-volatile coal.
10. Some evidence suggests that substantial proportions of certain Illinois coals can be used in four- and five-component blends with fine anthracites to produce suitable cokes.

11. Tests and experiments indicate that, in addition to the importance of superficial surface of the additive in blending, intrinsic (surface) properties of fine anthracites may be a significant factor.

#### Reasons against Blending Anthracite.

In listing potential disadvantages of blending anthracite fines, Clendenin and Kohlberg<sup>1</sup> carefully refer to them as "those most commonly put forth" as distinguished from their having been developed in the investigation at hand. Nevertheless, the following do represent the opinion of many coke-plant operators as to possible disadvantages:

1. The yield of gas and coal chemicals—tar, light oil, and ammonia—is decreased when fine anthracites are used.
2. The yield of coke breeze is increased.
3. The abrasion strength or hardness of the coke as measured in the tumbler test is usually decreased.
4. The ash content of the coke may be or is assumed to be increased.
5. Additional coal-handling problems arise, including those with wet and frozen fines; windage losses increase; and an additional bin and extra equipment are needed for the additional component.
6. Possible alteration of the cell structure of the coke and changes in coke porosity may occur.
7. Yield of salable coke is decreased when coke must be crushed for production of smaller sizes.

Similarly, as with reasons in favor of blending the fine sizes of anthracite, most of these may be applied with equal force to the blending of coke breeze.

Clendenin and Kohlberg<sup>1</sup> discuss these reasons against blending in some detail; and, though the following are not quotes, they may be said to summarize their findings: (1) It is admitted that anthracite has no residual value with respect to tar, ammonia, and light oil, but the net decrease in yields is very slight where small proportions of anthracite are used. (2) The increase in breeze yield is probably true, but it is felt that it can be controlled by careful anthracite selection, pulverization, blend-

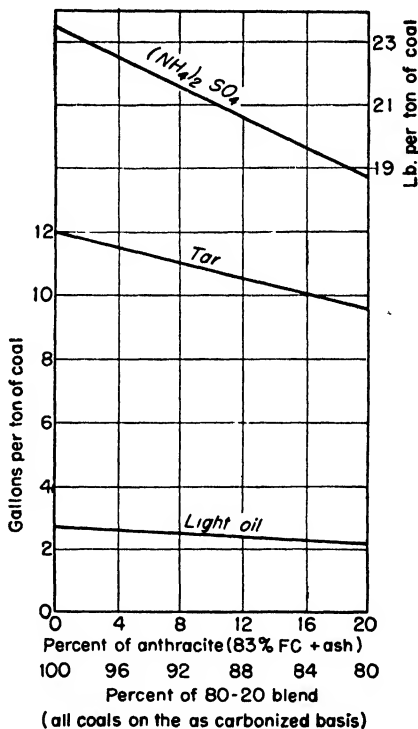


FIG. 6-10. Effect of anthracite on yields of by-products from a blend of 80 per cent Powellton and 20 per cent Pocahontas No. 4. (Clendenin, Barclay, and Wright.)

<sup>1</sup> Loc. cit.

ing, etc. (3) The strength and hardness are affected by blending but can undoubtedly be influenced by care in mixing, experience in blending, and other factors that will be gained by continued experience. (4) Increase in ash content is felt to be more apparent than real, since it may be in the order of only about  $\frac{1}{10}$  of 1 per cent. (5) Handling problems depend entirely on local plant conditions. (6) Charges that anthracite has a deleterious effect on cell structure would seem to be without serious basis in fact. (7) Decreased yield of salable coke where crushing is practiced is a real objection but has no bearing where crushing is not needed.

**Type of Anthracite Suited.** The proper selection of a suitable anthracite is an important consideration. The use of anthracites of a soft, friable, or decrepitating nature is to be avoided. A hard anthracite, free from undesirable friability and decrepitation, should be used.

Although anthracite fines may contain a high percentage of ash, the preparation of No. 5 buckwheat size generally produces a product which is suitable for blending purposes; and, where the percentage of anthracite does not exceed about 10 per cent, no marked increase in the ash content of the coke is produced. Replacing a bituminous-coal blend, which produces coke containing from 5 to 8 per cent ash, with anthracite containing 83 per cent fixed carbon plus ash, will, for each per cent of anthracite replacing the bituminous-coal blend, result in the following increases in the ash content of the resultant coke:

Per Cent Ash in Anthracite	Per Cent Increase in Ash per 1 Per Cent Anthracite Used
10	0 06
15	0 14
20	0 20

The ash content of coke made from coal blends of bituminous and anthracite is expressed more flexibly in the following equation:

$$\text{Per cent ash in coke} = \frac{(A \times a) + (B \times b) + (C \times c)}{(A \times X) + (B \times Y) + (C \times Z)}$$

where *A*, *B*, and *C* refer to the percentages of the component coals used in the coking blend

*a*, *b*, and *c* refer to the ash contents of the original coals

*X*, *Y*, and *Z* refer to the percentages of coke from the component coals when coked individually

**Impurities.** No difficulty should be experienced with the sulphur and phosphorus in anthracite, because these elements are present in amounts smaller than those usually found in bituminous coking coals. Since the ash-fusion temperature of anthracite ash is usually high, no trouble is likely to be encountered.

**Sizing.** Recently it has been shown that anthracite fines of No. 5 buckwheat size (approximately 20 by 100 mesh), will produce a satisfactory blend for foundry and, possibly, blast-furnace use. It is essential that oversize anthracite particles be absent, since they tend to cause points of weakness in the coke.

**Thorough Mixing Essential.** One of the principal causes of poor results in the carbonization of mixtures of anthracite fines and coking bituminous coals is the failure to mix the component fuels intimately. The anthracite particles must be thoroughly dispersed throughout the bituminous coal if satisfactory agglomeration of the mass is to be obtained. Segregation of anthracite frequently produces localized weaknesses in the coke.

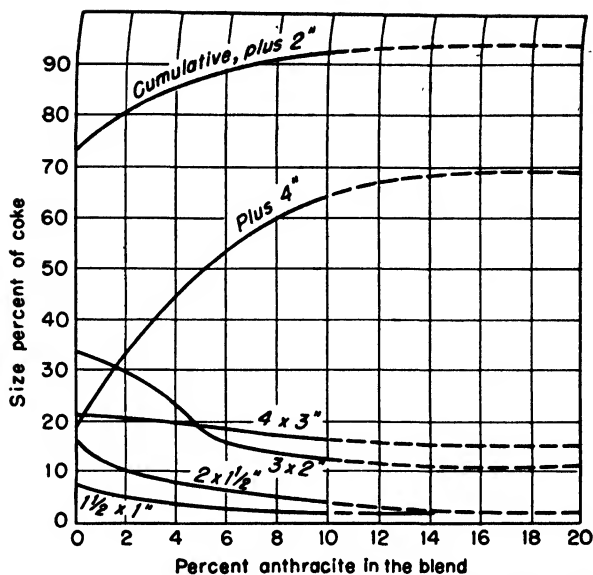


FIG. 6-11. Relation between per cent of anthracite in blend and size distribution of the coke. (Clendenin, Barclay, and Wright.)

Table 6-17. Effect of Anthracite on Physical and Chemical Properties of Coke<sup>1</sup>

Test No.	I	II	III
Blend, per cent:			
High-volatile bituminous...	75	75	80
Low-volatile bituminous. . . . .	25	20	15
Anthracite . . . . .	0	5	5
Coal blend analyses:			
Moisture, per cent . . . . .	4.1	4.6	4.6
Volatile, per cent.....	29.4	28.1	28.4
Ash, per cent . . . . .	7.2	7.5	7.7
Sulphur, per cent . . . . .	0.63	0.57	0.61
Analyses of coke:			
Volatile, per cent... . . . .	0.3	0.4	0.3
Ash, per cent . . . . .	8.9	9.0	8.8
Sulphur, per cent... . . . .	0.52	0.48	0.49
Screen test (run of oven):			
On 3½-in., per cent.....	28.0	55.6	45.1
On 3-in., per cent.....	49.0	72.2	60.8
Sp gr of coke:			
Apparent.....	0.94	1.01	0.98
True . . . . .	1.91	1.83	1.87
Porosity, per cent . . . . .	51.1	45.3	47.8
Shatter index (foundry size) cumulative per cent on 2 in..	74.2	89.0	84.0

<sup>1</sup> CLENDENIN, BARCLAY, and WRIGHT, *loc. cit.*

The coking time reported in each of these tests was 16.8 hr, in 17-in. ovens.

## PETROLEUM COKE<sup>1</sup>

Petroleum coke is the residual from the distillation of oil. In continuous or batch stills, and in certain points in other refining processes, coke builds up on the bottom

<sup>1</sup> MANTELL, C. L., "Industrial Carbon," 2d ed., pp. 219-222, D. Van Nostrand Company, Inc., New York, 1946.

or hottest part of the heated shell and is periodically removed during shutdown periods. Petroleum coke consists largely of pure carbon with small percentages of ash, probably from impurities and fine sand in the crude, and varying percentages of undesirable sulphur, depending on the source of the crude. (Sulphur from Mexican crude is usually high.) Petroleum coke is shiny and oily in appearance, hard and brittle.

Since petroleum coke is a "manufactured" by-product, its composition and size vary considerably as with the type of crude, the type of still, the process, the temperatures in the still, and the location of the coke in the still. For instance, coke formed adjacent to the shell of the still is known as "shell coke," and it is usually higher in ash

Table 6-18. Typical Analyses and Grindability of Petroleum Cokes<sup>1</sup>

Type of coke	Process	Volatile matter	Fixed carbon	Ash	Fusing temp	Grind-ability
Petroleum pitch.....	Holmes Manley	59 10	40 70	0 20	2185	175
	Dubbs	14 00	85 75	0 25	..	140
	Holmes Manley or Badger	7 70	92 00	0 30	2150	128
	Dubbs	14 40	83 35	2 25	..	127
Cracking still.....	..	12 20	85 75	0 25	..	123
Pressure still .....	..	15 35	84 05	0 60	2555	120
Cracking still .....	..	8 00	90 10	1 90	2160	108
	Dubbs	8 95	90 45	0 60	2095	106
Coke-still coke.....	..	11 95	87 60	0 45	1975	103
Coke breeze .....	..	10 05	89 39	0 60	2000	102
Hard-lump coke.....	..	9 15	90 65	0 20	2060	99
	Dubbs	10 42	88 78	0 80	1995	90
	Holmes Manley	10 90	88 55	0 55	1970	87
	Dubbs	9 60	88 25	2 15	..	82
Coke-still breeze.....	..	10 70	87 85	1 45	1875	73
Coke-still coke .....	..	6 65	93 20	0 15	2030	73
Coke-still coke .....	Isom	10 76	81 39	1 71	..	71
Coke-still coke .....	..	8 30	91 05	0 65	2055	63
Pressure still .....	..	12 10	86 60	1 30	2535	58
Stack petroleum coke	..	12 30	86 85	0 85	2160	57
Coke-still breeze	..	8 80	90 85	0 35	2090	47
Coke-still coke .....	..	13 70	86 20	0 10	2070	46
Coking mixture of re-duced coke ..	..	9 80	89 35	0 85	2025	46
Coke-still coke ..	..	6 35	91 35	2 30	2220	45
Coke-still coke ..	..	4 90	95 45	0 05	..	42
Coke heel .....	..	5 95	89 05	5 00	2025	37
Cracking-coil coke ..	..	6 80	92 90	0 60	2460	37
Coke-still coke ..	..	6 20	93 75	0 05	..	35
Stack coke ..	..	7 95	91 90	0 15	2950	33
Coke-still coke .....	..	2 95	96 85	0 20	..	31
Caustic-tar butts ..	..	13 50	80 10	6 40	..	25

<sup>1</sup> HARGROVE, R. M., Grindability of Coal, *Trans. ASME*, 1931, p. 43.

and soluble salts than coke formed higher in the still, probably because of a mechanical separation of these solids during formation.

The low ash content of petroleum coke is frequently a disadvantage when it is used as a fuel on grates, since, without the protective coating of the relatively cool ash, grates are very likely to burn and warp at a much greater rate than with higher ash fuels. Asphaltic coke, as produced in cracking units, varies in volatile according to its location in the still. It is friable and dirty to handle, and frequently degrades to powder on weathering. This type of coke is thus unsuited to lump burning, but it is suited to firing in pulverized form.

On the other hand, coke from batch stills usually consists of a large percentage of carboid coke, which withstands handling and transportation and is thus suited to

bulk firing as well as being in considerable demand for the production of electrodes and various industrial carbons.

It has been found that coke derived from paraffin-base oils graphitizes to a lower resistivity and gives a more unctuous graphite. This coke is usually preferred for industrial carbons. On the other hand, coke from asphaltic-base oils calcines and graphitizes to higher resistances and is apt to be a stronger, more abrasive material. Brush manufacturers take advantage of these differences to produce various grades of product.

Asphaltic coke and carboid coke are separate and distinct products, almost as different as coal and coal coke. The two types are distinguished by their content of volatile matter and asphaltenes.

### Retort Carbon, or "Glance" Coal<sup>1</sup>

Retort carbon, or "glance" coal, is a very dense form of carbon, produced by the deposition of carbon in the upper part of the retorts in the manufacture of coal and water gas. It exhibits the luster of a metal, is sonorous when struck, and is a good conductor. Ordinarily it is rich in silica, the result of adhering fragments of brickwork from the retorts. The amount of retort carbon on the market is very small.

Because of the small quantities as well as the high price, retort carbon is seldom used in making electrodes; its greatest use is in the manufacture of carbon brushes, where its hardness and the sharp edges of its particles are employed to give a cutting grain to the texture of the brush and a degree of abrasiveness after graphitizing.

### Pitch Coke<sup>2</sup>

Pitch coke is produced as the result of the destructive distillation of pitch, which comes mostly from coal tar. It has much the same properties as petroleum coke. It is low in ash and high in fixed carbon. In every place where petroleum coke is used it can be replaced by pitch coke. As the supply of petroleum coke grows less, because of changed methods of oil distillation, its place will probably be filled by pitch coke. What is needed is the production of a pitch coke with a volatile matter so low (0.5 per cent) that it needs no calcination.

## FUEL BRIQUETTES<sup>3</sup>

Fuel briquetting, a term applied to processes for agglutinating fine sizes of coal, lignite, or other fuels so as to make composite larger sizes, has as its principal objective beneficiation of the fuel by providing a resultant size that can be more readily handled and burned in conventional equipment.

Stillman lists the *following materials as being adaptable to beneficiation through briquetting*: peat, lignite, bituminous coal, anthracite, charcoal, coke breeze, sawdust, wood waste, lampblack, petroleum coke, lignite char, bagasse, straw, husks, shells, grain hulls, seeds, and wood chips.

Commercially anthracite, bituminous coal, brown coal (Europe), and lignite account for virtually all the briquetted tonnage, any of the others being for special purposes or local disposal.

Heat, pressure, binders, or combinations of the three are the mediums employed for securing the necessary cohesion, the choice depending almost entirely upon the raw materials used and the stability of the product desired.

<sup>1</sup> MANTELL, C. L., *op. cit.*, p. 222.

<sup>2</sup> MANTELL, C. L., *op. cit.*, pp. 219-222.

<sup>3</sup> MITCHELL, DAVID R., editor, "Coal Preparation," p. 565, AIME, New York, 1943. STILLMAN, ALBERT L., "Briquetting," The Chemical Publishing Company, Inc., Brooklyn, 1923. "Minerals Yearbook," U.S. Bureau of Mines, 1945, 1946.

**Binders Required.** In Europe, brown coals have been briquetted for years without binders. Similarly, some bituminous coals may be briquetted by heat and pressure alone without a binder, while others cannot. Briquetting anthracite without a binder is impossible, since it is noncoking and does not become plastic when heated. American lignites usually require binders and, in fact, are most satisfactorily briquetted after having been carbonized or reduced to char. (It has been asserted that some Canadian lignites may be satisfactorily briquetted without binders.)

Currently only one out of the 35 briquetting plants in the United States is attempting to briquette either bituminous or anthracitic coals without a binder, and in this

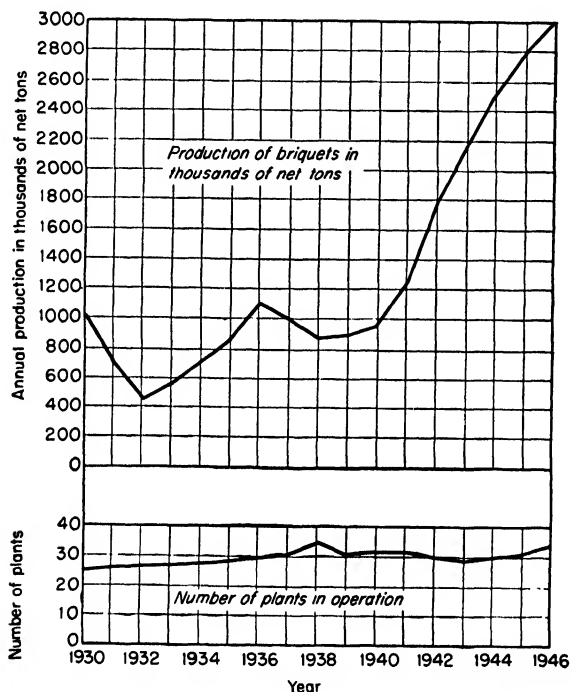


FIG. 6-12. Production of briquettes and plants in operation. ("Minerals Yearbook," U.S. Bureau of Mines, 1945.)

instance the output (from low-volatile bituminous coal) is used locally so that an optimum degree of stability may not be required.

**Binder Materials.** While a wide variety of materials has been both tried and used as binders for briquettes,<sup>1</sup> the American briquetting industry has virtually standardized upon petroleum asphalt. Several refining companies are in a position to furnish products especially for this purpose which have (1) good cementing strength, (2) water resistance, (3) toughness, and (4) freedom from sulphur and paraffin. The usual weight percentage of binder to raw coal is 5 to 7 per cent.

It is sometimes advantageous to use two binders, a main or "primary" binder as added to the dried and preheated coal such as asphalt, coal tar, or pitch; and a "secondary" binder such as flour or starch, added as either a paste or dry and heated with the coal in a preheater, to reduce appreciably the quantity of bituminous binder.

<sup>1</sup> STILLMAN, ALBERT L., "Briquetting," Chemical Publishing Company, Inc., Brooklyn, 1923, gives a very complete discussion of various binder materials and their effectiveness.

The briquettes are stronger and cleaner and produce less smoke than when asphalt alone is used.

Some processes, notably the *Hite process*, use the starch as a primary binder, and pitch as the secondary binder, to act as a waterproofing agent, since starch is not waterproof.

**Sulphite liquor** is sometimes used as a binder; but, although it produces a strong clean briquette, it is not waterproof. Carbonizing for 20 min at 600°F will char the sulphite liquor and produce a weatherproof briquette but will also weaken it.

In **briquetting anthracite**, the use of either coal-tar pitch or asphalt alone, as a binder, produces sufficient smoke to make the product inferior to the raw coal. Some process like the Hite process to reduce the amount of asphalt required is thus advisable. Even so, it is frequently difficult to produce a satisfactory briquette from some of the harder types of Pennsylvania anthracite, so that some bituminous coal is usually added.

When using flour paste, the large quantity of water required necessitates drying the briquettes at a temperature of 250°F before they are suitable for marketing.

**Table 6-19. World Production of Fuel Briquettes<sup>1</sup>**  
(In metric tons)

Country	1939	1944	1945	1946
Algeria	103,470	85,000	101,756	98,320
Australia (Victoria)	421,254	435,727	462,380	512,349
Belgium.....	1,561,210	456,990	787,530	"
Bulgaria....	88,496	"	"	"
Canada.....	62,242	277,707	275,625	298,960
Czechoslovakia: coal	508,000	464,000	"	"
Lignite	333,000	328,000	"	"
Eire ....	"	123,749	118,558	"
France...	8,364,000	1,588,490	3,531,530	5,399,430
Germany: coal	6,950,000	6,418,000	"	"
Lignite	44,930,000	61,549,000	"	"
Hungary: coal	509,300	"	"	"
Lignite	51,600	20,450	13,450	33,670
Indo-China, French	185,400	17,600	"	"
Italy.....	83,052	"	"	"
Netherlands: coal	1,268,926	608,316	412,571	725,859
Lignite	68,607	42,959	35,757	43,655
Netherlands Indies	85,079	"	"	"
New Zealand	29,889	12,661	9,941	13,183
Poland.....	465,390	765,217	93,078	529,084
Portugal.....	"	"	72,177	"
Rumania.....	245,487	"	"	"
Spain.....	789,815	924,862	1,049,520	"
Tunisia.....	83,989	1,430	16,619	32,347
Turkey.....	14,792	34,276	23,692	"
United Kingdom	813,810	883,974	1,002,333	1,567,664
United States: briquettes	809,398	2,236,163	2,505,816	2,725,193
Packaged fuel	195,504	159,455	188,823	173,198
Yugoslavia.....	132,466	"	"	"
Totals <sup>b</sup> .....	69,158,000	77,434,000	"	"

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1945.

<sup>a</sup> Data not available.

<sup>b</sup> Reported totals for other years are as shown below:

1936	1937	1938	1940	1941	1942	1943
57,255,064	64,633,680	64,821,366	70,374,000	74,304,000	73,515,000	78,511,000



### Manufacture of Fuel Briquettes in the United States<sup>1</sup>

The output of fuel briquettes in 1946, rising steadily since 1938, reached a new high of 3,004,027 net tons. Briquettes were made in 15 states with Wisconsin leading (1,511,670 tons), followed by Pennsylvania, West Virginia, and Missouri in that order. Thirty-five plants reported production in 1946 with locations as shown in Table 6-20.

**Table 6-20. Location of Briquetting Plants in the United States<sup>1</sup>**

Location	Number of plants	Avg capacity, net tons	Avg production, net tons
Eastern states . . .	7	220,000	126,000
Central states	25	114,000	79,000
Pacific states	3	48,000	46,000
Avg per plant (capacity and production)		130,000	86,000

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946.

**Raw Fuels Used.** Table 6-21 shows the wide variety of raw fuels used in the manufacture of fuel briquettes in 1946. The major fuels used are bituminous coal and Pennsylvania anthracite. The former, however, decreased in the period 1942-1946 from 65 to 45 per cent, while the use of anthracite rose in this period from 16 to 39 per cent.

**Table 6-21. Raw Fuels Used in Briquetting Plants<sup>1</sup>**

Fuel	Plants	Net tons (1946)	Fuel	Plants	Net tons (1946)
Pennsylvania anthracite	15	1,098,999	Lignite char	1 }	
Arkansas anthracitic coals	10	275,245	Residual carbon from gas	3 }	153,900
Bituminous (low-volatile)	17	1,166,043	Petroleum coke	3	15,053
Bituminous (high-volatile)	4	119,356	Total . . .	35 <sup>a</sup>	2,828,596

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946.

<sup>a</sup> Seventeen plants used one kind of fuel only 2 plants used 2 kinds separately, and 16 used mixtures of 2 kinds; hence the sum of the items shown exceeds the number of plants.

**Binders.** Asphalt binders remain the preferred type in briquetting coal and coke and were used exclusively by 30 plants that produced 92 per cent of the fuel briquettes made in 1946. Three other plants used (1) asphalt and coal-tar pitch combined, (2) asphalt and starch combined, and (3) oil-gas tar pitch. In 1946, two plants used no binder, one briquetted the carbon residue from the manufacture of oil gas, and one briquetted relatively small quantities of low-volatile bituminous coal for local consumption.

**Weight and Shape.** Pillow-shaped briquettes weighing less than 5 oz (except for an 11-oz, high-volatile bituminous-coal pillow made by Coal Processing Corp., Buckner, Ill.) were made at 32 of the 35 plants in 1946 and comprised approximately 77 per cent of the total production. Cylindrical (barrel-shaped) briquettes were made at two plants, and 18- and 20-oz cubes at one plant. Briquettes weighing under 3 oz represented 62 per cent of the total production in 1946.

<sup>1</sup> GOODMAN, GERTRUDE S., Fuel Briquets and Packaged Fuel Section, "Minerals Yearbook," U.S. Bureau of Mines, 1946.

**Table 6-22. Percentage of Binder Used in Briquetting Plants<sup>1</sup>**

Percentage of binder (by weight)	Plants	1946 production	
		Net tons	Per cent
No binder . . . . .	2 }		
Less than 5. . . . .	3 }	141,352	4 7
5 to less than 7. . . .	16	2,180,090	72 6
7 to less than 9. . . .	9	620,287	20 6
9 or more. . . . .	5	62,298	2 1
Totals. . . . .	35	3,004,027	100 0

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946.

**Table 6-23. Prevailing Weight of Briquettes Produced in 1945<sup>1</sup>**

Weight, oz	Plants	1945 production	
		Net tons	Per cent
Less than 2. . . . .	3	34,306	1 2
2 and less than 3. . .	16	1,648,244	59 7
3 and less than 4 . . .	6	669,513	24 2
4 and less than 5 . . .	5		
10 and less than 16 . .	1	410,141	14 9
16 and less than 25 . .	1		
Totals	32	2,762,204	100 0

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1945.

### Briquetting Lignite

Despite extensive experimental and field work, it is generally agreed that raw lignite, even when dried, is not a good briquetting material. Whether made with or without a binder, such briquettes seldom withstand weathering. In burning, the light volatile matter distills rapidly, causing the briquette to disintegrate long before combustion is complete. As a result, much of the unburned material drops to the ashpit, and the balance remains to choke the grates.

According to E. J. Babcock,<sup>1</sup> the most satisfactory, if not the only successful, method of briquetting lignite is first to carbonize the raw lignite, so as to remove at least a large proportion of the volatile gases as well as the moisture. The residue, relieved of its excess of light gas, becomes excellent material for briquetting (see Lignite, page 101, for further data on char).

**Carbonizing Lignite for Briquettes.** According to S. M. Darling, formerly of the U.S. Bureau of Mines, the following points should be observed in making lignite char for briquetting:

1. The carbonized lignite must be cooled, after distillation, without access of air. Dumped from the retort, the char ignites immediately, and quenching is extremely difficult.

2. Lower temperatures than are usual in gas practice are to be preferred in lignite distillation. Thus a greater yield of liquid products, of higher value, is obtained.

3. A continuous process of retorting is desirable, and the fact that lignite crumbles during carbonization facilitates the design of such an installation.

4. Because of the crumbling during carbonization, practically all the carbon output of a lignite retort must be briquetted, especially if the product is desired for household purposes.

According to the U.S. Bureau of Mines,<sup>2</sup> variations in the size to which the char is crushed, and the evenness of the crushing, decidedly affect the character of the briquettes.

A finished product with as little void space as possible is desirable; hence if the percentage of the larger sized particles is excessive, either a large percentage of binder must be used or the briquette will be weak. Briquettes made with a char sized as in Table 6-24 were found to be strong and in every way satisfactory.

Uniform feeding of lignite char and binder is absolutely essential. Preferably, it should be automatic.

<sup>1</sup> BABCOCK, E. J., *U.S. Bur. Mines Bull.* 89.

<sup>2</sup> "Investigations of the Preparation and Use of Lignite," *U.S. Bur. Mines Bull.* 255.

**Binders and Admixtures Used.** According to J. E. Mills,<sup>1</sup> asphalt, pitch, and combined bituminous and flour binders are perhaps the best. Where flour was used, the indications were that 1 per cent of flour replaced 2 per cent of bituminous binder; however, the proportion cannot exceed a certain limit because flour or starch alone is not a waterproof binder. If too much bituminous is used, the briquettes burn with a smoky flame and soften as they become heated; if not enough binder is used, they will be weak and handle poorly. With an excess of flour, they tend to mold under certain conditions.

**Table 6-24. Screen Analysis of Lignite Char for Briquetting**  
(Size of char particles)

Through	Over	Per cent
10	20	30.6
20	30	28.8
30	40	26.4
40	60	13.4
60	..	0.8
Total.....		100.0

Professor E. J. Babcock, of the North Dakota School of Mines, found that, in the process of gas manufacture, 15 lb of tar could be obtained from 1 ton of dry lignite, which, when added to the briquette mixture, would cut down the necessary pitch admixture to 4 per cent.

The usual percentages of asphalt or pitch binders range from 5 to 9 per cent, admixtures of coking coal from 0 to 15 per cent, and of flour from 0 to 2 per cent. All permutations of these ingredients have been used, with the degree of success depending

**Table 6-25. Comparative Crushing, Abrasion, and Absorption Tests of Lignite-char Briquettes and Other Coals<sup>1</sup>**

Kind of fuel	Crushing strength, psi	Abrasion, per cent	Absorption after 48 hr immersion, per cent
Lignite-char briquettes:			
Fresh (6 carloads).....	1,050-1,600	6.1-11.4	9 3-18.9
6 weeks, outside storage (2 samples)	1,050, 1,120	12 7	11 2, 13.5
6 months, outside storage (3 samples)	1,353-1,479	2.4-16.9	14 5-16.0
1 year, inside storage . . .	1,403	7.0	18.1
Anthracite.....	3,950		
Youghiogheny bituminous coal	2,595	5.1	1.0
Pocahontas bituminous coal	1,903	19 1	4.2

<sup>1</sup> "Investigations of the Preparation and Use of Lignite," *U.S. Bur Mines Bull.* 255, p. 113.

**Table 6-26. Comparative Drop Tests on Lignite Char Briquettes and Other Coals<sup>1</sup>**

Kind of fuel	Between 2 and 1½ in., per cent	Between 1½ and ¾ in., per cent	Finer than ¾ in., per cent
Lignite-char briquettes (11 samples)...	92.5-97.5	1.25-3.13	1.25-4.37
Youghiogheny bituminous.....	82 5	15.63	1.87
Pocahontas bituminous.....	58.1	18.15	13.75

<sup>1</sup> *U.S. Bur. Mines Bull.* 255, p. 114.

largely upon the results needed. Professor Babcock reports excellent briquettes with 5 to 6 per cent pitch, 5 per cent of bituminous coal, and 1 to 2 per cent of flour or grain screenings. Abrasion, crushing strength, and other properties are as shown in Tables 6-25 and 6-26.

<sup>1</sup> MILLS, J. E., "Binders for Coal Briquets," *U.S. Bur. Mines Bull.* 24, 1911.

Differences in the temperature of the char and the binder have a marked effect upon the blending of the two. Optimum results have been reported at 160 to 165°F, a higher temperature than is customary with other fuels.

Successful results have been obtained when the moisture content of the ground carbonized lignite was 8 to 14 per cent in the mix.

**Yield of Lignite Briquettes.** According to the *U.S. Bureau of Mines Bulletin 255*, the yield of briquettes to a ton of lignite can be readily determined when the yield of residue (char) is known. For example, if, upon carbonizing, 43.5 per cent or 870 lb of char is obtained from a ton of raw lignite, the yield of briquettes containing 9 per cent binder and 5 per cent moisture will be  $\frac{870 \times 100}{100 - (9 + 5)}$ , or 1,012 lb per ton, equiv-

alent to 50.6 per cent of the raw lignite used. (If the lignite had been carbonized merely to expel the water, the yield of the particular lignite used in the example would have been 71.8 per cent to represent the maximum possible yield in processing this particular lignite to char with no combustion in the retorts.)

**Analysis and Properties of Lignite Briquettes.** While the properties of lignite briquettes depend entirely upon such variables as the lignite used, char, binder, and processing, lignite briquettes can be made that are hard, sufficiently resistant to storage and handling, and that burn similarly to anthracite, with the exception, possibly, of some smoking when fresh fuel is added to the fire.

Table 6-27. Comparison of Properties of Briquettes and Raw Lignite<sup>1</sup>

	Briquetted lignite char	Raw lignite
Ability to endure open-air storage .....	Good	Slacks decidedly
Liability to spontaneous combustion.....	Apparently none	Considerable
Size .....	Uniform	Not uniform
Approx heat value, Btu .....	12,000	6,000-7,000
Attention required to control rate of combustion ..	Very little	Considerable
Fuel loss due to difficulty in controlling the fire ..	Slight	Appreciable
Fuel loss due to fines passing through the grates ..	Very little	Appreciable
Loss in weight as sustained by dealers.....	Approx same as anthracite	Considerably more than anthracite
Relative amount of storage for equal heat values ....	1 volume	1.7 volumes
Relative freight on amounts of same heat value. ..	1	1.7
Per cent of ash.....	12-16	7
Relative frequency of charging fuel into heater	1	Almost 2

<sup>1</sup> From *U.S. Bur. Mines Bull. 255*, p. 109.

\* Because of the higher heating value of the briquettes and the difference in combustion efficiencies, the actual quantity of ash formed for a definite quantity of recovered heat is not greater with briquettes than with raw lignite.

Table 6-27 can be used in comparing the composition, heating value, character, and general utility of the lignite briquettes with other fuels. The degree to which lignite is benefited by carbonization is also shown.

Table 6-28 is a follow-through of lignite-char briquettes, all made from the same lignite. Part of the volatile matter was purposely left in the briquettes with the intent of making them adapted to a wider range of use. The percentage of volatile could have been reduced by further carbonization had this been desired. The variation in composition between the char and the briquettes is chiefly due to the introduction of the binder, which is high in volatile and low in fixed carbon, and also to the fact that in briquetting a little moisture is necessarily added to the dry char.

The calorific value of the briquettes is almost double that of the original lignite.

Table 6-28. Comparative Analyses of Lignite, Char, and Briquettes<sup>1</sup>

Fuel	No. of samples <sup>a</sup>	Moisture, per cent	Volatile matter, per cent	Fixed carbon, per cent	Ash, per cent	Sulphur, per cent	Btu per lb
Lignite.....	7	36.9	28.8	28.9	5.4	0.67	6,563
Char.....	10	0.8	13.0	72.3	13.9	1.14	11,697
Briquettes.....	9	3.3	20.2	64.4	12.1	1.09	11,682

<sup>1</sup> "Investigations of the Preparation and Use of Lignite," *U.S. Bur. Mines Bull.* 255, p. 113.

<sup>a</sup> Each sample represents a carload lot.

### Briquetting Charcoal

Stillman describes two methods of converting comminuted wood into by-products and charcoal. One calls for the distillation of the wood in its finely divided form to make a resultant finely divided charcoal which is then subsequently briquetted; the other calls for briquetting the wood waste and distilling the briquettes. The first method has the advantage of great rapidity in production of by-products and charcoal, but the charcoal must be briquetted, and the briquettes, if wood-tar binder is used, should be subjected to a carbonization or distillation process for the removal of that binder. He says that it is a proper method of procedure where a good serviceable metallurgical charcoal is desired and that the charcoal briquette so secured is far better than the usual block-charcoal product.

### PACKAGED FUEL

Since 1928, a form of briquette has been available on the domestic-fuel market, in which lightly compressed cubes of raw coal or screenings and a binder, usually starch, are wrapped and sealed in heavy paper for convenient firing.

The difference between this "packaged fuel" and briquettes is mainly in that:

1. The cubes are larger than most briquettes, being from 3 to 5 in. on a side, and weighing up to about 3 lb each.
2. The blocks are not so hard, being formed under relatively low pressure with a starch binder. (Some operators use cement, although this increases the ash content of the cubes.)
3. The cubes are neither weatherproof nor structurally strong, for, being wrapped, there is not the same need for stability.
4. The blocks are wrapped in heavy paper, intended for firing without opening the package to separate the six cubes commonly contained therein. Packages weigh from 10 to 15 lb.

**Advantages of packaged fuel**, as cited by the C. M. Eberling Co., principal manufacturers of the machinery used for packaging, include:

1. The total smoking period of packaged fuel, as compared with 3- by 5-in. egg coal from the same high-volatile coal, is reduced by one-half; and the amount of smoke produced is less than that of the egg at the point of maximum smoking.
2. Packaged-fuel cubes may be processed so that the coal may be burned with no more accumulation of soot than from much lower volatile coals.
3. Packages can be stacked close to the furnace without the necessity for a coalbin. Shoveling is unnecessary, and handling is clean. One or two packages are usually sufficient for a charge.

Cubes made largely from anthracite to the same sizing specifications as had been used for bituminous were reportedly much too large for the average domestic furnaces. As any breaking of the cubes or even opening of the packages defeats much of the

purpose of packaged coal, it is believed that any resumption of effort to package anthracite should consider the standard of egg coal as a guide to maximum cube sizing ( $2\frac{7}{16}$  by  $3\frac{1}{4}$  in.).

Table 6-29. Annual Capacity and Production of Packaged-fuel Plants<sup>1</sup>

### Manufacture of Packaged Fuel in the United States<sup>1</sup>

**Processes.** As of 1946, 65 of the 70 active operations used the Eberling process (Cleveland, Ohio), 3 used Glenn-Smith equipment (rights held by Blaw-Knox Co., Pittsburgh), and two used Johnson equipment (Johnson Coal Cubing Co., Detroit, Mich.).<sup>2</sup>

**Binders.** Per cent of binder in packaged fuel, by weight, ranged from 0.5 to 5.0 per cent. Starch, averaging about 15 lb per ton of packaged fuel produced, is the principal type of binder used and was exclusively employed by 65 of the total of 70 plants, producing 73 per cent of the total output. Asphalt, averaging 89 lb per ton of packaged fuel, was employed exclusively by 3 plants (two using low-volatile bituminous and one a combination of low-volatile bituminous and Pennsylvania anthracite). A combination of asphalt and starch in the manufacture of petroleum-coke cubes was used at 1 plant, and cement was used at 2 plants.

The Eberling and Johnson processes generally employ a starch binder. The Glenn-Smith process uses an asphalt binder, making cubes which are also sold in bulk (unwrapped).

**Raw Fuel and Product.** Of a total of 187,666 tons of six types of fuel used as raw materials, 171,116 tons, or 91 per cent, was low-volatile bituminous as used at 67 plants. The other five fuels were medium- and high-volatile bituminous, anthracite, semianthracite, and petroleum coke.

Of the eight straight and mixed fuel products produced, 165,734 tons out of 190,919, or 86.8 per cent, were exclusively low-volatile bituminous coal.

Year	Number of plants	Annual capacity, net tons	Annual production, net tons
1937	64	456,000	146,037
1938	76	500,000	160,952
1939	103	700,000	215,507
1940	106	777,000	284,513
1941	103	698,000	269,844
1942	89	630,000	253,048
1943	72	460,000	215,605
1944	68	428,600	175,770
1945	61	452,320	208,143
1946	70 <sup>a</sup>	530,760	190,919

<sup>1</sup> "Minerals Yearbook," U.S. Bureau of Mines, 1946.

<sup>a</sup> Of the 70 active plants in 1946, 42 had a capacity of less than 5,000 tons and 17 between 5,000 and 10,000 tons.

### PELLETIZING ANTHRACITE FINES

The Anthracite Institute, with the help of The Pennsylvania State College, has done considerable work on the agglomeration of anthracite fines through extrusion from a "sausage-grinder" type of machine. While this work has not, as yet, reached the "handbook" stage, Paul A. Mulcey, director, Anthracite Institute Laboratory, and J. W. Eckerd presented a series of descriptive papers at the 1947, 1948, and 1949 Anthracite Conferences of Lehigh University. Mulcey and Eckerd's conclusions include:

1. Pellets, which are sufficiently resistant to impact and abrasion to withstand at least nominal handling, can be extruded from high-ash anthracite fines in an auger press without an added binder.

2. The critical factors affecting the quality of extruded pellets are: (a) mixing, the most important factor to control and the most difficult to attain; (b) ash content,

<sup>1</sup> GOODMAN, GERTRUDE S., *loc. cit.*

<sup>2</sup> These processes are discussed by V. F. PARRY, Technical and Economic study of Packaged Fuel, U.S. Bur. Mines Repts. Invest. 3757, 1944.

with the strength of the pellets increasing in proportion to the ash content; (c) moisture content; and (d) size consist.

3. Anthracite pellets ignited readily, maintained combustion at very low rates, burned out, and passed through grates without degradation to excessive dust, and were considered particularly suitable for traveling-grate stokers ( $\frac{1}{8}$ - and  $\frac{3}{16}$ -in. pellets) as well as for small equipment where moderate burning rates, very low banking rates, and high acceleration are desirable ( $\frac{3}{8}$ - to  $\frac{3}{4}$ -in. pellets).

4. At least 50 per cent of the extrusion moisture must be removed for satisfactory handling, such as by radiant drying.

5. Pellets extruded without a binder are subject to degradation in water, hence should be protected or waterproofed. "Masonex" was found an excellent binder for strength though not waterproof; cutback asphalt had limited binding qualities, with quantities above 3 per cent being undesirable because of smoke and odor. Water-gas tars were not satisfactory.

6. Burning rate of pellets increases with diameter and seems increased by small amounts of charcoal and some binders. Rate of heat release increases with ash content.

7. The extrusion machine must have a barrel for high working pressures and a ratio of die thickness to port diameter of 4:1.

8. Power consumption was as low as 6 kw/hr per ton, with small quantities of surface-active agents facilitating extrusion.

## **SECTION 2**

### **LIQUID AND GASEOUS FUELS AND MISCELLANEOUS SOURCES OF HEAT AND POWER**





## CHAPTER 7

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### PETROLEUM AND PETROLEUM DERIVATIVES

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## PETROLEUM<sup>1</sup>

As early as 3000 B.C. the Persians used an asphaltic pitch to impregnate torches for their illuminating systems. This pitch probably came from weathered crude oil recovered from surface seepage. Statuary, sculptured from asphalt, has also been identified with this period.

From that very early date until the nineteenth century, very minor quantities of petroleum were used. Then sperm oil, used in lamps as an illuminating oil, became in short supply, and the destructive distillation of coal for "coal oil" was developed. At about the same time, crude petroleum, then called "rock oil," was being recovered from surface seepage and sold by itinerant medicine men as a patent medicine. The "coal-oil" refiners tried petroleum in their equipment and found that they could produce a greatly superior lamp oil.

Because the original skimming of crude petroleum from lakes and pools was a rather costly procedure, Drake and his colleagues drilled the first discovery well in Pennsylvania in 1859 to start a vast new industry. From such a modest beginning, we are now producing more than 5,000,000 bbl per day, which represents some 65 to 70 per cent of the world's production. Venezuela, the next largest producer at 1,000,000 bbl per day, represents some 15 per cent. The Middle East produces only 770,000 bbl per day but has vast reserves and a large undeveloped area.

### COMPOSITION OF PETROLEUM

Basically, petroleum is a mixture of hydrocarbons, *i.e.*, of molecules which contain only carbon and hydrogen. In addition, there are always impurities such as sulphur

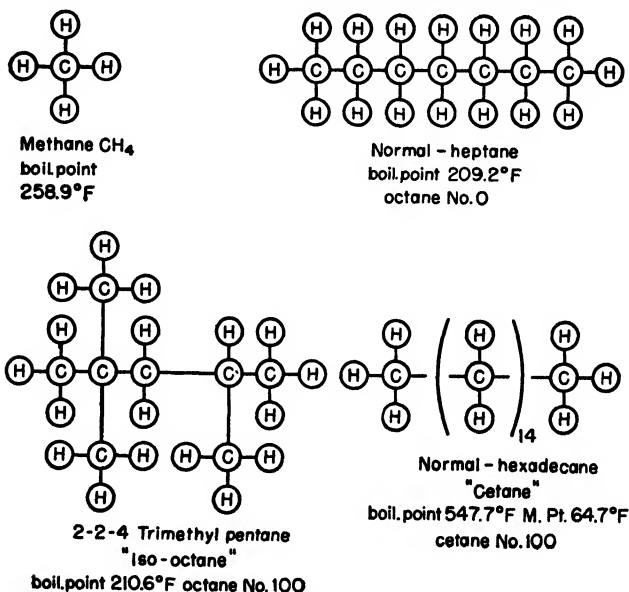


FIG. 7-1. Molecular structure—paraffin series hydrocarbons. (C. A. Rehbein, ASME, 1948.)

<sup>1</sup> REHBEIN, C. A., Production of Diesel Fuel Oils, "Diesel Fuel Oils," p. 6, ASME, 1948.

and nitrogen compounds and even metallic compounds such as derivatives of vanadium, found to an appreciable extent in some Venezuela oils.

However, hydrocarbons are susceptible to virtually unlimited permutations and combinations of the carbon and hydrogen atoms, ranging from the simplest form, methane or marsh gas, to the most intricate groupings and interconnections of the basic four atoms of hydrogen centered around an atom of carbon. As each permutation and combination produces a product of different characteristics, the field of discussion of hydrocarbons is absolutely unlimited, and the discussion of even the known fuels resulting from the many combinations is far beyond the scope of a handbook.

In general, crude oils vary in composition with respect to the paraffin, naphthene, and aromatic groups, and this fact is a basis for their classification. While crudes are usually named for their geographical location, their characteristics depend upon chemical composition. All crude oils are really a mixture of the three groups; none has been found that is purely one series. The most paraffinic comes from Pennsylvania and is well known for its lubricating-oil content. California and the Asiatic area around the Caspian Sea produce oils rich in naphthenes. The aromatic-asphaltic type is represented by natural asphalt as found in Lake Trinidad.

#### Characterization or Base of Crude Oils<sup>1</sup>

The three structural types of hydrocarbons present in all fuel oils are paraffins, naphthenes, and aromatics. The proportions of these differ greatly in crudes from different sources. Several rather arbitrary designations used to distinguish the various types of crudes express comparative rather than absolute characteristics.

**Paraffin-base crudes** are composed principally of paraffins in the lighter fractions and of alkyl naphthenes in the heavier fractions. They always contain "paraffin wax," which is not, however, composed solely of paraffin hydrocarbons. The asphalt content may range from a mere trace to an appreciable quantity. The sulphur content is relatively low. The specific gravity and viscosity are both rather low, and the proportions of straight-run gasoline and of kerosene are usually high. These crudes occur chiefly in the Eastern parts of the United States. Pennsylvania and West Virginia crudes are all of this type.

**Mixed-base crudes** are lower in normal paraffins and higher in naphthenes than are the paraffin-base oils. Sulphur and asphalt contents are higher on the average. Mixed-base crudes contain wax, but their specific gravities and viscosities of the corresponding fractions are higher than for paraffin-base materials. Mid-Continent crudes are of the mixed-base type.

**Naphthene-base crudes** are characterized by a high percentage of naphthenes, a relatively high specific gravity, and the virtual absence of wax. They may be sub-classified into light and heavy groups, the light crudes containing a relatively high proportion of gasoline and little asphalt, with the heavy crudes containing little gasoline and high percentages of asphalt. Distillate from a heavy-naphthene crude is similar or identical in general properties to that from a light crude. Various naphthene crudes have widely different sulphur contents. They occur in Central, South Central, and Southwestern areas of the United States.

The term **asphalt base** is very indefinite and is not recommended for classifying crudes.

**Aromatic crudes** contain a relatively high percentage of the lower aromatic hydrocarbons. This type occurs chiefly in the state of California and often has a fairly low

<sup>1</sup> GRISWOLD, JOHN, "Fuels, Combustion, and Furnaces," pp. 32, 33, McGraw-Hill Book Company, Inc., New York, 1946.

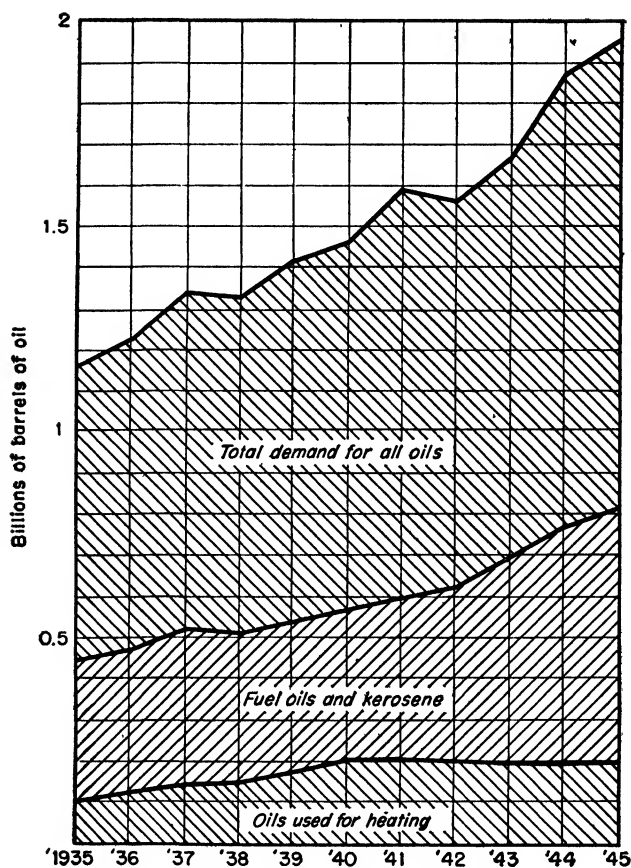


FIG. 7-2. Total demand for all oils.

specific gravity because of a high proportion of material in the lower molecular weight or gasoline range.

The U.S. Bureau of Mines procedure for testing crude oils includes a **Hempel** distillation upon the sample, which is then classified as paraffin, naphthene, or inter-

Table 7-1. Relative Cost of Transporting Oil by Various Methods<sup>1</sup>

Type transportation	Ton-miles	Per cent	Cost per ton-mile
Water.....	10,378,739,263	87.92	\$0.00063
Railroad.....	244,358,433	2.07	0.01640
Pipe line (crude)	744,174,990	6.30	0.00477
Pipe lines (gasoline)	372,992,210	3.16	0.00527
Trucks.....	64,219,988	0.55	0.04873
Total..	11,804,484,884	100.00	\$0.00162

<sup>1</sup> Testimony (Pew) before Temporary National Economic Committee, Part 14, Petroleum Industry, Sec. 1, September, 1939.

**NOTE:** In 1939 there were no pipe lines of a diameter equal to the Big Inch lines. As the volume of products pumped through a pipe line varies as the square of the diameter, it is obvious that the costs would be materially lower in the larger lines.

mediate base according to specific gravities of fractions of designated boiling ranges. The UOP characterization factor is also most useful for classifying and correlating the properties of oils. Devised by the Universal Oil Products Co., it is defined as the

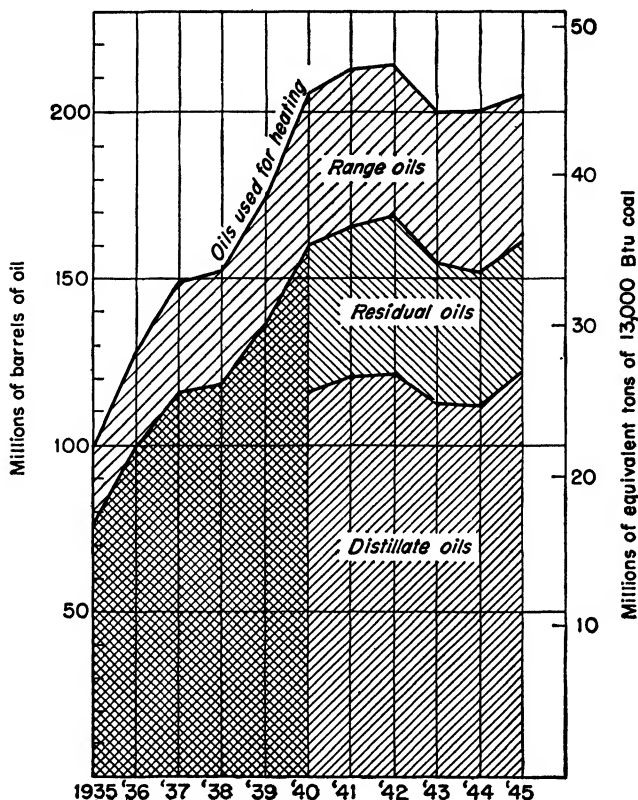


FIG. 7-3. Consumption of heating oils.

ratio of the cube root of the average boiling point in degrees Rankine to the specific gravity at 60°F. Numerical values range from about 12.5 for paraffin stocks to 10.0 for aromatics.

### SCOPE OF FUEL-OIL SPECIFICATIONS<sup>1</sup>

1. These specifications cover five grades of fuel oil for various types of fuel-oil-burning equipment.

2. The fuel oils herein specified shall be hydrocarbon oils free from acid, grit, and fibrous or other foreign matter likely to clog or injure the burner or valves. If required, the oil shall be strained by being drawn through filters of wire gauze of 16 meshes to the inch (U.S. Standard sieve 16, ASTM 1,190 microns). The clearance area through the strainers shall be at least twice the area of the suction pipe, and the strainers shall be in duplicate.

3. The various grades of fuel oil shall conform to the detailed requirements shown in Table 7-2. It is the intent of these classifications that failure to meet any require-

<sup>1</sup> Referring to NBS, "Detailed Requirements for Fuel Oils," CS12-48, Sept. 25, 1948. See Table 7-2

**Table 7-2. NBS Commercial Standards Specifications for Fuel Oils<sup>a</sup> CS12-48**  
(Effective Sept. 25, 1948. Replacing Standard CS12-40)

Grade of fuel oil	Description	Flash point, deg F min	Pour point, deg F max	Water sediment, per cent by volume, max	Carbon residue on 10 per cent, max	Ash, per cent by weight, max	Distillation temp, deg F		Saybolt viscosity, sec		Kinematic viscosity, centistokes			Grav-ity, deg API, min	Corro-sion, copper strip, 3 hr at 122°F
							10 per cent point, max	90 per cent point, max	Universal at 100°F	Furl at 122°F	Max	Min	At 100°F	At 122°F	
No. 1	A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal	0	Trace	0.15	...	420	...	...	...	2.2	1.4	...	...	35
No. 2	A distillate oil for general-purpose domestic heating for use in burners not requiring No. 1 fuel oil	100 or legal	20 <sup>d</sup>	0.10	0.35	...	...	675	40	...	(4.3)	...	...	...	26
No. 4	An oil for burner installations not equipped with preheating facilities	130 or legal	20	0.50	...	0.10	...	...	125	45	(26.4)	(5.8)	...	...	
No. 5	A residual-type oil for burner installation equipped with preheating facilities	130 or legal	...	1.00	...	0.10	...	...	...	150	40	...	...	(81)	
No. 6	An oil for use in burners equipped with preheaters permitting a high viscosity fuel	150	...	2.00 <sup>f</sup>	...	...	...	...	...	300	45	...	...	(638) (92)	

<sup>a</sup> Recognizing the necessity for low sulphur fuel oils used in connection with heat-treatment, nonferrous metal, glass and ceramic furnaces, and other special uses, a sulphur requirement may be specified in accordance with the following table:

Grade of Fuel Oil		Sulphur, Max. Per Cent	
No. 1	No. 2	No. 5	No. 6
0.05	0.10	...	...
1.0	No limit	...	...

<sup>b</sup> Other sulphur limits may be specified only by mutual agreement between the purchaser and the seller.

<sup>c</sup> It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

<sup>d</sup> Lower exposed copper strip shall show no gray or black deposit.

<sup>e</sup> Lower or higher pour points may be specified whenever required by conditions of storage or use. However, these specifications shall not require a pour point lower than 0°F under any conditions.

<sup>f</sup> The 10 per cent point may be specified at 440°F maximum for use in other than atomizing burners. The amount of sediment by extraction shall not exceed 2.00 per cent. The amount of water by distillation plus the sediment in quantity shall be made for all water and sediment in excess of 1.0 per cent. A reduction in quantity shall be made for all water and sediment in excess of 1.0 per cent.

ment of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

4. The technical requirements of NBS Commercial Standard CS12-48 are identical in substance with Tentative Specifications for Fuel Oils, ASTM D396-48T.

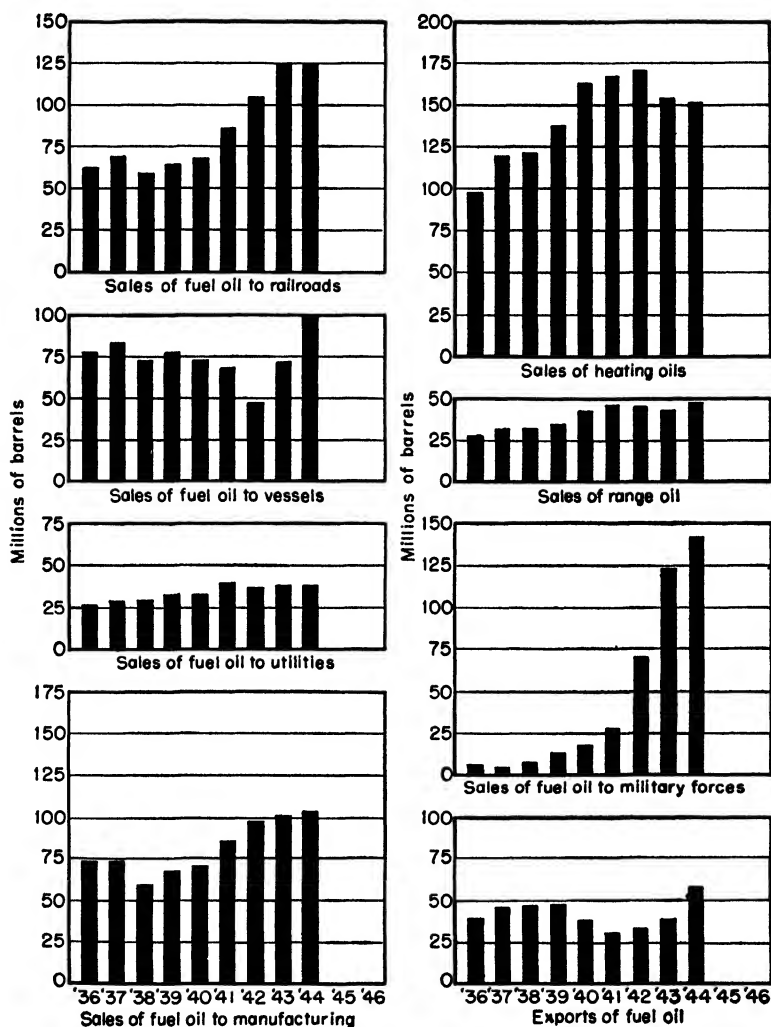


FIG. 7-4. Sale of fuel oil by uses.

#### Pacific Coast Fuel-oil Designations

In the Pacific Coast states, a somewhat different designation is used for distillate and residual fuel oils than in the remainder of the United States. In place of the 1, 2, 4, 5, and 6 oils, the Pacific states oils are numbered PS-100, PS-200, PS-300, and PS-400.

According to the Western Oil and Gas Association, the uses and specifications are as follows:



**PS-100.** A distillate oil for use in stoves, space heaters, burners for distillate burning, spark-ignition engines requiring a volatile fuel, and commonly described as stove distillate or stove oil.

**PS-200.** A distillate oil for use in furnaces, burners, diesel or semidiesel engines requiring a low-viscosity, moderately volatile fuel, and commonly described as diesel fuel oil, or burner oil.

**PS-300.** A residual oil for use without preheating in furnaces and burners requiring a low viscosity fuel, and commonly described as light fuel oil, domestic fuel oil, or low-viscosity fuel oil.

**PS-400.** A residual oil for use in furnaces and burners equipped with preheaters permitting a high-viscosity fuel, and commonly described as industrial fuel oil, heavy fuel oil, or high-viscosity fuel oil.

**NOTE:** Intermediate grades of oil to be designated as the lower Pacific Specifications number. (No mention of sulphur specification.)

**Gravities Corresponding to Pacific Specifications.** While no gravities are officially specified for any of the oils listed under the Pacific Standards, The Western Oil and Gas Association advises that experience indicates fairly close ranges of API gravities:

	<i>Deg API</i>
PS-100... ..	35-39
PS-200... ..	28-31
PS-300... ..	10-15
PS-400... ..	7-17

**Notes on the General Classification of Fuel Oils** (Table 7-4). API gravities 0 to 13 are extremely heavy oils (0 to 9 being heavier than water) which require constant heat in the tank and circulation in the pipes to the burners. These oils are semisolid at normal temperatures. They are sold as "still bottoms," "45 per cent asphalt," "heavy bunker C," and similar designations. Preheat suggested 220 to 260°F.

API gravity 10 corresponds to water in weight and specific gravity.

**Blending Fuel Oils**<sup>1</sup> (Table 7-5). Although it is common practice at the refineries to mix two or more oils to produce a blend of a different grade, this is a phase that usually requires considerable study and experimentation for the production of a desirable product. The heavy residual oils have a tendency to deposit sludge in storage; this may be aggravated by mixing oils of different character, as even when deliveries from two sources go into the same tank. To avoid trouble, it is wise to establish the compatibility of the oils in question. This may be accomplished by simply mixing the oils and centrifuging to determine whether the bottom sediment is increased appreciably.

The distillate fuels are produced at the refinery from cracked, cracked and straight-run, and straight-run sources. Careful refining methods are utilized to make products with a high degree of stability to prevent deposits from gum or sludge. To avoid trouble, the following very general rules will be helpful:

1. Straight-run residuals can be mixed with any straight-run product.
2. Thermal cracked distillates are unstable when blended with straight-run and tend to form gum. These mixtures are not normally produced by a refiner.
3. The catalytic cracked distillates are stable fuel distillates, either alone or blended with straight-run distillates that do not contain appreciable quantities of active sulphur compounds or organic acids.
4. Straight-run residuals can be mixed with cracked distillates.
5. Cracked residuals should be blended with cracked distillates rather than straight-run distillates.
6. Cracked distillate can be added as a third ingredient to mixtures of all straight-run products (item 1).

<sup>1</sup> Checked by correspondence with R. D. Bent, Research and Development Department, The Atlantic Refining Co., Philadelphia.

**Table 7-3. Pacific Specifications for Fuel Oils**

PS No.	Flash point, deg F		Water and sediment, per cent	Viscosity, sec		Distillation temp			
						10 % point		90 % point	
	Max	Min	Max	Max	Min	Max	Min	Max	Min
PS-100. . . . .	165	110 <sup>a</sup>	0 25	...	...	420	350	550	450
PS-200. ....		150	0 50	55 <sup>b</sup>	35 <sup>b</sup>	...	425	...	600
PS-300 . . . .		150	1 00	40 <sup>c</sup>	25 <sup>c</sup>				
PS-400. . . . .		150	2 00	.	60 <sup>c</sup>				

<sup>a</sup> Or legal.<sup>b</sup> Seconds Saybolt Universal at 100°F.<sup>c</sup> Seconds Saybolt Furol at 122°F.**Table 7-4. General Classification of Fuel Oils<sup>a</sup>**

(With range of gravities, heat values, and comparison of old specifications, CS12-40, with those of Sept. 25, 1948, CS12-48)

Trade No.	Principal use	Present specifications, CS12-48			Former specifications, CS12-40		
		Gravity, deg API	Lb/gal	Btu/gal	Gravity, deg API	Lb/gal	Btu/gal
1	A distillate oil intended for vaporizing pot-type burners and other uses requiring a volatile fuel	35-40	6 879-7 085	135,800-138,800	38-40	6 879-6 960	135,800-137,000
2	A distillate oil for general-purpose domestic heating for use in burners not requiring No. 1. Moderately volatile	26-34	7 128-7 490	139,400-144,300	34-36	7 043-7 128	138,200-139,400
3	Formerly, a distillate oil for use in burners requiring a low-viscosity fuel. Now incorporated as part of new No 2 oil	.	.	.	28-32	7 215-7.396	140,600-143,100
4	An oil for burner installations not equipped with preheating facilities	24-25	7 538-7 587	145,000-145,600	24-26	7 490-7 587	144,300-145,600
5	A residual-type oil for burners equipped with preheating facilities. Sold as Bunker B. Preheat suggested 170 to 220°F	18-22	7 686-7 891	146,800-149,400	18-22	7.686-7 891	146,800-149,400
6	An oil for use in burners equipped with preheaters permitting a high-viscosity fuel. Bunker C. Preheat suggested 220 to 260°F	14-16	7 998-8.108	150,700-152,000	14-16	7.998-8 108	150,700-152,000

<sup>a</sup> As gravities are not included in commercial standards (excepting minimum gravities of 35 for No. 1 oil and 26 for No 2 oil) this table is unofficial, based on trade practices under code CS12-40.**Codes Specified for Testing Fuel Oils<sup>1</sup>**

1. The requirements enumerated in the specifications CS12-48 (ASTM D396-48T) shall be determined in accordance with the following methods of testing of the ASTM, except as may be required under paragraph 2.

<sup>1</sup> For conformity to NBS CS12-48, and the identical ASTM D396-48T. Complete information regarding the procedure for making the tests specified, but not included in the tests below, is to be found in the publications of the ASTM.

Table 7-5. Check Chart for Blending Fuel Oils

	Distillates		Residuals	
	Straight	Cracked	Straight	Cracked
Distillates:				
Straight.....	No			
Thermal cracked..	Yes			
Catalytic cracked..				
Residuals:				
Straight . . . .	Yes	Yes		
Cracked .	No	Yes	Yes	

Body of chart shows whether it is generally well to mix oils shown at top and side.

**2. Flash Point.** The flash point, instrument, and method for determining minimum flash shall be those legally required for the locality in which the oil is sold. In the absence of legal requirements, the minimum flash point shall be determined in accordance with the Standard Method of Test for Flash Point by Means of the Pensky-Martens Closed Tester, ASTM D93-46.

**3. Pour Point.** Standard Method of Test for Cloud and Pour Points, ASTM D97-47.

**4. Water and Sediment** (for Grades 1 to 5, inclusive). Tentative Method of Test for Water and Sediment in Petroleum Products by Means of Centrifuge, ASTM D96-47T.

**Water by Distillation** (for Grade 6). Standard Method of Test for Water in Petroleum Products and Other Bituminous Materials, ASTM D95-46.

**Sediment by Extraction** (for Grade 6). Tentative Method of Test for Sediment in Fuel Oil by Extraction, ASTM D473-46T.

**5. Carbon Residue.** Standard Method of Test for Carbon Residue of Petroleum Products (Ramsbottom Carbon Residue), ASTM D524-42.

**6. Ash.** Standard Method of Test for Ash Content of Petroleum Oils, ASTM D482-46.

**7. Distillation.** Distillation of Grade 1 oil shall be made in accordance with the Standard Method of Test for Distillation of Gasoline, Naphtha, Kerosene, and Other Similar Petroleum Products, ASTM D158-41.

**8. Viscosity.** Kinematic Viscosity for Grade 1, Tentative Method of Test for Kinematic Viscosity, ASTM D445-46T. Saybolt viscosity for grades 2, 3, 4, 5, and 6. Standard Method of Test for Viscosity by Means of the Saybolt Viscosimeter, ASTM D88-44.

**9. Gravity.** Standard Method of Test for Gravity of Petroleum and Petroleum Products by Means of the Hydrometer. ASTM D287-39.

**10. Corrosion.** Standard Method of Test for Detection of Free Sulphur and Corrosive Sulphur Compounds in Gasoline, ASTM D130-30 (except for interpretation of exposed copper strip).

#### PETROLEUM TERMS, TESTS, AND CHARACTERISTICS AND SIGNIFICANCE OF TESTS ON PETROLEUM PRODUCTS<sup>1</sup>

The utility of petroleum products depends to a large extent upon their physical characteristics, since petroleum is an extremely complex raw material. Not only is

<sup>1</sup> "The Significance of Tests of Petroleum Products," ASTM, Philadelphia, 1946. Abstracted by permission of ASTM. For a more comprehensive description of the significance of tests on petroleum, see latest current edition of the above. For methods of testing, see specific tests of ASTM as, for instance, those listed in Table 7-7.

Table 7-6. Typical Properties of Petroleum Products<sup>1</sup>

	Gasolines		Fuel-oil-blending stocks					Distillate fuel oils		
	House brand	Premium	Dry-treated light gas oil	Acid-treated heavy-weight gas oil	Untreated heavy-weight gas oil	Acid-treated thermally cracked gas oil	NaOH-treated catalytically cracked gas oil	Kerosene	No. 2 fuel oil	Premium diesel oil
Gravity, API, @ 60°F.	63	63	39.7	33.8	36.2	35.5	24.5	41.9	35.0	37.1
Color, NFA scale No.	..	..	1	2	2	2	1.5	+28 Say	2	2
Initial boiling point, deg F.	92	91	340	380	458	342	430	336	368	360
Distillation:										
10% recovered at deg F.	121	118	389	437	510	389	482	370	425	426
50% recovered at deg F.	215	208	426	518	552	454	520	437	505	502
90% recovered at deg F.	320	330	510	614	601	549	570	510	591	585
End point, deg F.	397	410	574	674	647	622	610	546	651	646
Recovery, per cent	..	..	99.0	99.0	99.0	99.0	99.0	130(TCC) <sup>2</sup>	170	164
Flash (F-M), deg F.	..	..	148	190	200+	160	200+	..	35.1	35.1
Flash (F-M), deg F.	..	..	32.0	37.7	39.5	32.6	35.7	..	48.4	55.8
Viscosity, Saybolt sec, @ 100°F.	..	..	55.0	48.0	60.0	41.3	38.0	..	0.55	0.41
Viscosity, centistoke, @ 100°F.	..	..	0.58	1.01	0.18	0.55	0.82	0.037	0.55	0.41
Diesel index	..	0.087	..	..	..	..	..	..	..	..
Sulphur, per cent	0.1	81	50	47	58	40	37	..	47	52
Octane No., ASTM	76	..	0.16	0.07	0.025	0.22	0.25	0.01	0.11	0.07
Cetane No., ASTM	..	..	..	..	..	..	..	..	..	..
Conradson carbon residue, (10 per cent bottoms)	..	..	..	..	..	..	..	..	..	..
Gum, ASTM mg/100 ml	2	1	..	..	..	..	..	..	..	..

<sup>1</sup> Compiled from "Diesel Fuel Oils," pp. 21-23, ASME, 1948.

<sup>2</sup> Pensky-Martens closed tester (ASTM D93-42).

<sup>3</sup> Tag closed-cup tester (ASTM D56-36).

little really known about its chemistry, but such chemical tests as do exist serve principally to protect against undesirable constituents or impurities. However, there are a number of physical tests that are useful to consumers as an index to the value or fitness of products for particular uses.

The proper choice of tests and the assignment of proper numerical values to specifications based on these tests is of fundamental importance. Failure to meet this requirement tends to increase the cost of the product to the consumer and adds to the burdens of the manufacturer.

Table 7-7 lists the more common tests by products to which they are most frequently applied, and the following paragraphs give a brief synopsis of the significance or importance of each test.

**Table 7-7. Usual Application of Various Tests on Petroleum Products<sup>1</sup>**

(A, test usually made. B, test sometimes made)

Name of test	Principal ASTM test code	Crude petroleum	Gasoline and naphtha	Illuminating oil	Fuel oil and gas oil	Lubricating oil	Transformer oil	Grease	Paraffin wax	Petrolatum
Acidity (in gasoline)	D235-39	B	B							
Autogenous ignition temp.	D286-30	B	B	B	B	B	B			
Burning quality (illuminating oils)	Various		A							
Carbon residue . . . . .	D189-41			B	B	A				
Cloud and pour points. . . . .	D97-39	B		B	A	A	A			
Color (also D155-45T) . . . . .	D156-38		A	A	B	A	A		A	B
Consistency . . . . .	D217-44T									
Corrosion . . . . .	D130-30		A	A	B	B	B	A		A
Dielectric strength . . . . .	D117-43					A				
Dilution (crankcase oil) . . . . .	D322-35					A				
Doctor test . . . . .			A	A						
Emulsification . . . . .	D157-36				B	A	A			
Flock test . . . . .				B						
Gravity . . . . .	D287-39	A	A	A	A	A	A			
Grease analysis . . . . .	D129-40							A		
Gum (in gasoline) . . . . .	D381-44		A							
Knock characteristics . . . . .	D357-45		A							
Melting point of wax . . . . .	D87-42								A	
Melting point of petrolatum . . . . .	D127-30					B	B			A
Neutralization No. . . . .	D188-27T									
Oil and moisture (in wax) . . . . .	D308-29T								A	
Oxidation at high temp . . . . .						B	A			
Precipitation . . . . .	D91-40					A				
Protection test . . . . .						B				B
Saponification No. . . . .	D94-45					B				
Sulphur . . . . .	Various	A	A	A	A	B				
Thermal value . . . . .	D240-39		B	B	B					
Viscosity . . . . .	Various	B	B	B	A	A	A			
Volatility:										
Flash and fire tests	Various	B	B	A	A	A	A			
Distillation tests	D86-45	A	A	A	A	B				
Vapor-pressure and evaporation	D323-43	B	A							
Water and sediment . . . . .	D96-40	A			A	B				
Wick-feed test . . . . .										

<sup>1</sup> "The Significance of Tests of Petroleum Products," p. 2, ASTM, Philadelphia, 1946.

**Acidity** (in gasoline). Only acid which could normally be present is sulphuric, which is one of the chemicals used in the refining process. Essentially a refiner's test, as a positive indication rarely occurs with products which have been released to the consumer. Presence of free acid obviously an indication of improper refining.

**Autogenous Ignition Temperature.** The temperature of a metal bath just adequate to cause ignition of a mixture of vapor and air. A difficult test requiring careful and expert interpretation. Results are a close approximation of the minimum ignition temperature and thus are of fundamental value for indicating fire and explosive hazards and dangerous exposure limits. Used for indicating diesel ignition, subject to limitations of conditions of pressure, turbulence, and contamination with products of combustion.

**Burning Quality** (illuminating oils, kerosene). Largely practical tests to ensure satisfactory operation of oil on a wick burner. Such factors are stressed as ability to burn for long periods without attention; freedom from fouling the wicks, and provision of a strong flame that will not be extinguished by swinging lanterns. Satisfactory oils burn with constant size and shape of flame and without clouding or smoking the chimney. Obviously important where oil is to be used in wick burners for light or heat.

**Carbon Residue.** Some oils, upon distillation, leave a nonvolatile carbonaceous residue; others do not. Test originally developed for comparison of the carbon-forming properties of lubricating oils for internal-combustion engines. In the manufacture of gas from gas oil or fuel oil, carbon-residue content of the oil bears a relation to the quantity of carbonaceous residue deposited in the carbureting apparatus. Also important in connection with certain types of oil-burning equipment and heavy-oil internal-combustion engines. Values for carbon residues which are abnormally high in relation to other properties of the oil may indicate the presence of heavy residual products because of unsuitable refinery methods or contamination.

**Cloud and Pour Points.** Petroleum oils become more or less plastic solids when sufficiently cooled, because of either the partial separation of the wax or the congealing of the hydrocarbons composing the oil. With some oils, the separation of the wax becomes visible at temperatures slightly above the solidification point, which is then known as the "cloud" point. The point at which the oil just barely flows under prescribed conditions is known as the "pour point." Oils vary widely on these characteristics. The cloud point is of value in wick-feed service or where a haze or cloud would be objectionable. Pour-point specifications are included in order that oil may be secured which will not cause difficulty in handling or in use at the lowest temperatures to which it may be subjected.

The color of petroleum products is described and defined in terms of color by reflected light or by transmitted light. Color by reflected light in the case of lubricating oils is usually referred to as "bloom" or "fluorescence." Products on which color measurements are made range from the practically colorless to these which appear opaque when examined in the neck of a 4-oz oil-sample bottle. Commercial usage divides these products into two general classes: (1) so-called "white" products, which range from practically colorless to "pale straw," and, (2) "pale straw" and darker.

Color is important only for such special uses as dry-cleaners' naphtha, pharmaceutical, textiles, and technical white oils. Minor differences in oil color do not indicate any difference in burning characteristics. A prevalent fallacy is that pale color indicates low viscosity. Color of wax, always determined in the molten wax, is important.

**Consistency.** Generally considered to refer to the flow-pressure characteristics of viscous liquids and of plastic materials, such as petrolatum, greases, soap-thickening oils, and pitches, which occupy an intermediate position between viscous liquids and plastic solids. Term consistency is sometimes used to include related factors which might more properly be described as differences in texture ("smooth," "fibrous," "spongy"), elasticity ("tacky," "rubbery"), or ductility ("stringy," "short," "cheesy"). The methods of utilizing both grease and petrolatum are so varied that

it is impossible to generalize on the significance of penetration data except to point out that the more fluid the grease the easier it can be fed to, or squeezed out of, a given bearing and the less the friction down to the point of its being squeezed out. For many of the uses of petrolatum, the penetration figure is a better measure of the properties desired than is the more widely used melting point, although the melting point is generally, but not always, roughly parallel to stiffness.

**Corrosion.** Tests usually involve contact with polished copper, although in some instances contact with iron or steel is specified as well. Tests and designations to indicate the corrosive properties of the product itself should not be confused with those intended to indicate the measure of **protection** from salt spray or water afforded by slushing oils, greases, etc. The ASTM corrosion test for gasoline intended as a safeguard against motor fuels which might attack the metal, is very satisfactory. The government corrosion test at 212°F, for lubricating oils, while not so widely used, seems to afford a proper degree of protection. The **copper-dish** test for motor gasoline should never be specified as it involves too many variables.

**Dielectric strength** refers to the value up to which the electrical stress must be brought in order to cause electrical breakdown. Usually expressed as voltage per unit length and stated in kilovolts per millimeter or in equivalent units. In test methods employing a single breakdown distance, "dielectric strength" is often applied simply to the voltage at which breakdown occurs. As applied to transformer, circuit breaker, and insulating oils, "dielectric strength" may be taken as an indication of the adequacy of the oils for the electrical stresses they are intended to resist. Test also useful for measuring effect of contamination, such as by water, dirt, and conducting particles.

**Dilution of crankcase oils** results from less volatile portion of the gasoline passing unburned into the crankcase. A function of both the quality of the gasoline and operating conditions. Presence of high-boiling constituents in gasoline tends to cause dilution; for any given gasoline dilution is governed by engine design and operation, the most important being crankcase and water-jacket temperatures. Significant effects of dilution are decrease in viscosity and increase in volatility of crankcase oil.

**Doctor Test.** A very sensitive chemical test for hydrogen sulphide and mercaptans (mercaptans are chemical compounds analogous to the alcohols or phenols but containing sulphur in place of oxygen). Contrary to general belief, the doctor test fails to indicate the presence of either free sulphur or total sulphur. For the detection of corrosive sulphur compounds, it is decidedly inferior to the copper-strip test.

**Emulsification.** The presence of small amounts of some other materials in water or oil decreases the natural rate of separation of the two materials and may prevent any separation whatever. This phenomenon is known as emulsification. For certain purposes, as the lubrication and cooling of certain metal tools and the lubrication of marine engines, it is desirable that the oil form a relatively stable emulsion with water; for other purposes, as in the lubrication of steam turbines, it is highly essential that any emulsion separate rapidly and completely. Accordingly, measurement of the rapidity of separation is of considerable value. Next to viscosity, it is the most important test for steam-turbine oils.

**Analysis of Grease.** The most important properties of a grease are physical and include suitable consistency and texture, proper heat resistance for a given purpose, freedom from corrosive action, and satisfactory film-forming and friction-reducing properties. Examination of the individual components of a grease analysis may indicate performance expectancy if the needs are well known; but, as interpretation is usually difficult, the principal value is to see that the grease is of the general type specified and that the variations between different lots and brands are not greater

than reasonable. Purchase specifications which include close numerical limits, based on an analysis of a particular grease, are unfair to the manufacturer and do not ensure the needed product.

**Gum Content.** Cracked gasoline, upon exposure to oxygen of the air, as in ordinary storage, may undergo oxidation, with the formation of undesirable compounds. These compounds are soluble in the gasoline unless a marked aging has taken place but, upon evaporation of the gasoline, form resinous materials which are insoluble in the gasoline. This residue, called "gum," is expressed in milligrams of gum per 100 ml of sample. Gasolines vary in gum stability and thus have varying gum contents after a given amount of aging. Similarly, a gasoline of given gum stability may form gum at varying rates depending upon the conditions of storage, such as temperature, access of air, and presence of catalytic materials. Test methods for gum are not too well developed or easy to interpret.

**Knock Characteristics of Motor Fuels.** *Octane Number.* It is believed that gasoline knock is due to the autoignition of a portion of the charge in front of the flame. The knock characteristic of a motor fuel is now considered one of its most important properties. To determine the octane number (or knock index) of a fuel, it is compared in a standard continuously variable compression engine, with mixtures of isooctane (2, 2, 4-trimethylpentane) and normal heptane. The ASTM octane number of a fuel is the percentage of isooctane (expressed as a whole number) in that mixture of isooctane with normal heptane which the motor fuel on test matches in knock characteristics when compared by the procedure specified. Since isooctane knocks less and heptane knocks more than any commercial gasoline, high-octane-number fuels will knock less than those with low octane numbers. While severe knocking may result in damage to pistons and bearings and loss of power, improvement of the fuel beyond the point necessary to eliminate the knock involves unnecessary expense, since it has been conclusively shown that such improvement does not increase the performance value of the fuel.

*Cetane number* is a test to measure ignition quality, principally of diesel oils. It is of considerable importance in cold-starting of diesel engines; not so important as other properties as the engine becomes heated. In general, the cetane number can be increased by increasing the average boiling point of the fuel mixture.

Cetane number has no quantitative significance; it tells only that fuel A is better than fuel B, but not how much better. To attach quantitative significance to the cetane number, it is necessary to study the performance of the fuel under the particular environment of use.

As cetane number indicates the ease of self-ignition, and octane number the resistance to self-ignition, it is evident that there is an inverse ratio between the two (Fig. 7-5).

*Diesel index* has also been used as a measure of ignition quality but is in no sense a replacement for cetane number.

$$\text{Diesel index} = \frac{\text{deg API} \times \text{aniline point (deg F)}}{100}$$

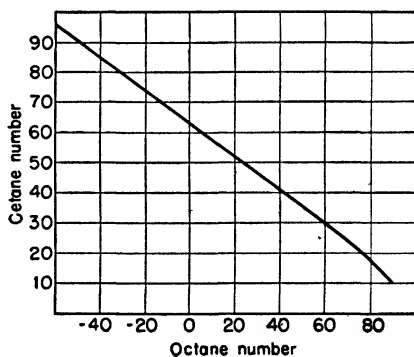


FIG. 7-5. Relation between octane and cetane numbers. (Martin A. Elliott, ASME, 1948.)



**Melting Point of Paraffin Wax and Petrolatum.** The melting point of paraffin wax is the temperature at which it changes from a liquid to a solid state; of petrolatum, the temperature at which it changes from a solid to a liquid condition. The melting point required for a wax depends entirely upon the purpose for which it is to be used.

**Neutralization Number.** Practically all petroleum lubricating oils contain substances which have acid characteristics. The proportion of these substances present in an oil is commonly referred to as its "organic acidity." The "neutralization number" of an oil is defined as the weight in milligrams of potassium hydroxide required to neutralize 1 g of oil.

While it is obvious that the effect of alkali or *mineral* acid in a petroleum oil is deleterious, the practical significance of "organic acidity" is complicated by such points as the fact that the neutralization numbers vary greatly with different crudes; *organic* acids normally present are not corrosive or harmful, and some contend that *organic* acids improve the friction-reducing qualities of an oil. It is thus evident that the general quality of an oil cannot be evaluated in terms of its neutralization number. Specifications should never include limits on this property unless it is known that an oil of low *organic* acidity is required.

**Expressible Oil and Moisture in Paraffin Waxes.** As wax is usually separated from the containing oil by repeated pressing at low temperatures, the amount of oil remaining in or carried through with the wax is a function of the refining process. Substantial freedom of the wax from oil is important in the case of wax for candles, sealing food products, and other cases where the contamination by exuded oil might be detrimental. While exact determinations are difficult, a test for the *expressible* oil and moisture (ASTM D308-29T) more nearly approximates the information desired than any other method.

**Oxidation at High Temperatures.** When petroleum oils deteriorate in service, this deterioration is generally accompanied by oxidation and the formation of oxidation products. In some types of service, such as the lubrication of steam turbines and the insulation and cooling of transformers, the ability of oil to resist chemical changes is of prime importance. For different types of service, different tests have been proposed. While some of the methods have been developed to a degree that the results are moderately reproducible, none has been correlated with service behavior to a point that permits standardization for universal use.

**Precipitation Tests.** Crude petroleum contains constituents which, for the want of a more definite description, are classed as "asphalt." Being nonvolatile, these are concentrated in the residual products. If the latter are to be used as lubricants, it is necessary to test for the content of asphaltic material.

The effect of "asphalt" content upon the lubricating qualities of an oil is not definitely known. For certain types of service, there is no question as to the unsuitability of oils which contain appreciable quantities of asphaltic constituents, but on the other hand the importance of moderate variations undoubtedly is exaggerated by many users. Filtered products, such as the so-called "bright stocks" largely used as the constituents of motor oils, contain negligible quantities of asphalt. Another group, which includes steam-refined cylinder stocks, is characterized by a moderate percentage of material that is insoluble in precipitate naphtha. So-called "black oils," which are used for such purposes as the lubrication of gears and car journals, usually show precipitation tests that are moderately high.

**Protection Test.** Certain petroleum products are used as coatings on metals as protection against corrosion. As both the conditions of exposure and the natural resistance of the metal may vary widely, no protection test has been developed which is applicable to all conditions. Such tests are essentially qualitative, and their interpretation depends largely upon the judgment of the observer.

The **saponification number** of a fatty or a compounded oil is the number of milligrams of potassium hydroxide required to saponify 1 g of the oil. It is a measure of both free and combined fatty acids. If it is desired to determine the amount of potassium hydroxide corresponding to the combined acids, it is necessary to subtract from the saponification number the amount of potassium hydroxide required to neutralize the free acids (see Neutralization Number).

Saponification numbers of the more common fats and fatty oils fall within the ranges shown in Table 7-8. Where the number is not known, it is customary to use 195.

**Volatility** may be defined as the tendency of a product to change from the state of a liquid to that of vapor. For petroleum products it is usually discussed under the following subdivisions: (1) flash and fire tests, (2) distillation tests, (3) vapor-pressure tests, and (4) evaporation test.

**Flash and Fire Tests.** The **flash point** of a liquid may be defined as the temperature to which it must be heated in order to give off sufficient vapor to form an inflammable mixture with air. The **fire point** may be defined as the temperature to which a product must be heated in order to burn continuously after the inflammable air-vapor mixture is once ignited. The fire-point test is the less frequently used, and in a majority of instances adds nothing to the information furnished by the flash test.

The flash points of petroleum products vary over a wide range. The more volatile gasolines and naphthas flash at temperatures considerably below 0°F. Certain naphthas, largely used as paint thinners and solvents, have closed-cup flash points between 80 and 110°F; kerosene 100 to 160°F; gas oils and fuel oils 150 to 300°F; and a majority of lubricating oils 275 to 650°F.

Flash point is universally regarded as the most important index of fire hazard, as well as being an index to the probabilities of ignition. Wide variations in the flash-point requirements are enforced by various municipalities. In the absence of local law, ASTM states that the usual minimum limit for the flash point of fuel or gas oils is 100°F for domestic installations and 150°F for industrial installations. The really important factor is that the user be thoroughly advised as to the material that he is handling so that proper precautionary measures may be used and that there be no sudden change in the flash point of materials supplied.

**Distillation tests** involve the general procedure of vaporizing the liquid and recording the relation between temperatures and quantity of distillate. As results are expressed in terms of a series of figures, expert interpretation is required.

Laboratory distillation under prescribed conditions gives an indication of the volatility and volatility range of the product. The 10 and 90 per cent points, frequently shown, represent the temperatures at which 10 per cent and 90 per cent of the product is distilled. The end point, usually also shown, is the maximum temperature recorded by the distillation thermometer when the distillation is 100 per cent complete.

The 10 per cent point serves as an index of the ease of ignition of the oil; the 90 per cent point and the **end point** are specified to make sure that the oil will volatilize and burn completely and produce a minimum amount of carbon.

**Table 7-8. Saponification Numbers of Commercial Fats and Fatty Oils<sup>1</sup>**

<i>Fats or Fatty Oils</i>	<i>Saponification No.<sup>2</sup></i>
Lard oil.....	192-198
Tallow.....	193-198
Neat's-foot oil.....	193-204
Fish oil.....	140-193
Sperm oil.....	120-140
Castor oil.....	176-187
Rapeseed oil.....	170-179
Soybean oil.....	189-197
Peanut oil.....	186-197
Cottonseed oil.....	191-197
Blown rapeseed oil.....	195-216
Blown cottonseed oil.....	210-225
Degras.....	110-210

<sup>1</sup>"The Significance of Tests of Petroleum Products," p. 37, ASTM, February, 1946.

<sup>2</sup>Saponification is defined as the decomposition of a fat by alkali, with the formation of a soap, or salt of the fatty acid.

The following generalities apply to the significance of distillation tests:

**Gasoline** should contain enough readily volatile constituents to permit starting the engine readily in cold weather; should not contain so large a percentage of highly volatile constituents as to result in excessive evaporation, premature vaporization, or vapor lock; and should not contain any considerable percentage of relatively heavy constituents which will not vaporize properly.

**Natural Gasoline.** Three factors of importance are: percentage distilling below 140°F, a reference point in blending; freedom from more than traces of absorbent oil, as covered by specifying maximum end point; and a minimum content of excessively volatile constituents, as covered by specifying a maximum vapor pressure.

**Kerosene.** Distillation does not yield much information except when necessary to ascertain the presence of fractions of high boiling point which may tend to clog or crust the wick of the burner. If used as an internal-combustion-engine fuel, requirements bear a similarity to those of gasoline.

**Gas Oils.** Most important function of distillation test is to determine its suitability for cracking. Of some use in conjunction with gravity and other fuels for establishing "cracking characteristics" for making carbureted water gas.

**Crude Oil and Partly Refined Stocks.** Distillation test useful for estimating yield and quality of finished product.

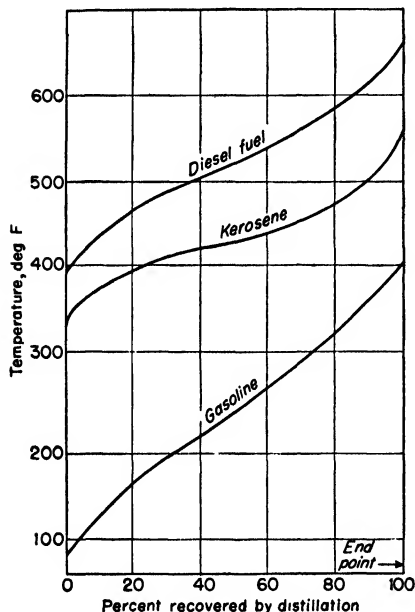


FIG. 7-6. Typical distillation curves for petroleum products.

of a pure liquid is equal to the standard atmosphere is the normal boiling point of the liquid.

The vapor pressure of mixtures of substances not only is a function of temperature but is also dependent on the composition. Each component of the mixture contributes to the total vapor pressure in proportion to its mol fraction and to the vapor pressure of the pure component at the temperature of measurement. Since by vaporization the composition of the liquid phase is changed, the vapor pressure of mixtures will vary with the volume of vapor space.

Vapor pressure as applied to gasolines is important as to a specification for volatility (in conjunction with distillation specifications), and for safety in transportation.

**Evaporation Test.** Specifications for lubricating oils occasionally include a requirement limiting the per cent evaporation after heating to a specified temperature for a specified time. Known as an evaporation test, the results are likely to be quite variable and inferior to the equally informative flash-point and fire-point tests. There would thus seem to be no justification for continuing this test.

**Water and Sediment.** One of the most important tests made on crude petroleum and some of its products. For fully refined petroleum products it is customary and

**Vapor-pressure Tests.** The vapor pressure of a substance is the term applied to that phenomenon which indicates the tendency of the substance to vaporize. Is generally expressed in terms of millimeters of mercury, pounds per square inch, or atmospheres. Vapor pressure increases with temperature, and the temperature at which the vapor pressure

practical to specify freedom from water and sediment, as indicated by the transparency and "bright" appearance of a 4-oz sample.

Water and sediment are impurities which are almost entirely excluded in fuel oils Nos. 1 and 2 and which are permitted in somewhat larger quantities in fuel oils Nos. 4, 5, and 6. It is difficult to eliminate them entirely from the latter group, and the advantage is not sufficient to justify the cost. Water and sediment are determined together by the centrifuge, except for grade 6.

**Ash.** The ash test is used to determine the amount of noncombustible materials in the oil. These impurities come principally from the natural salts present in the crude oil and from the chemicals used in the refining operations, although they may also come from scale and dirt picked up from containers and pipes. Some ash-producing impurities in fuel oil cause rapid deterioration of refractory materials in the combustion chamber, particularly at high temperatures; some are abrasive and destructive to pipes, pumps, valves, control equipment, and other burner parts.

**Wick-feed Test.** As reciprocating steam engines for marine service are lubricated by oil passing through wool wicks to moving parts, it is necessary that the oil contain no impurities that would clog the wicks.

### Viscosity

The viscosity of a fluid is the measure of its resistance to flow. The unit of absolute viscosity is the "poise," whereas the unit of kinetic viscosity is the "stoke."<sup>1</sup> The viscosity in poises of a given fluid is the product of the viscosity in stokes and the density at the temperature of test.

Viscosimeters designed so that the head of the liquid being tested is the sole force driving the liquid through the capillary measure kinematic viscosity, whereas those designed so that external forces produce the flow measure absolute viscosity. Viscosity is usually expressed in seconds of time for a given volume of liquid to flow through an orifice. This is true of the Saybolt, Redwood, and Engler viscosimeters.

The wide range of viscosities normally encountered is shown in Table 7-9.

As viscosity changes rapidly with temperature, a numerical value of viscosity has no significance unless the temperature is specified.

The *Saybolt Universal viscosimeter* is the most widely used method in the United States for the determination of the viscosity of lubricating oils (ASTM D88-44), although for purposes where greater accuracy is required the *ASTM Method of Test for Kinematic Viscosity (D445-42T)* is recommended. Standard temperatures of test for both methods are 100, 130, and 210°F. The lower temperatures are mostly used for the low-viscosity oils, and vice versa.

It should be stressed that Saybolt viscosities, which are expressed in seconds, are not even approximately proportional to absolute viscosities except in the range above 200 seconds. As the time of flow decreases, the deviation becomes more marked, and below 40 seconds the departure is so great that the use of Saybolt seconds as an index of absolute velocity is very deceptive. For example, an oil with a viscosity of 35 seconds Saybolt has about twice the absolute viscosity of one which gives a reading of 32 seconds Saybolt, and even the very lightest oils do not give readings below about

**Table 7-9. Approximate Absolute Viscosity of Various Liquids<sup>1</sup>**

(As measured at room temperature)	
Liquid	Poise
Hexane.....	0.003
Commercial gasoline ...	0.006
Water.....	0.01
Kerosene.....	0.02
Straw oil.....	0.4
Automobile lubricants .....	1-10
Cylinder stocks.....	40
Heavy fuel oils and liquid asphaltic road materials .....	100+

<sup>1</sup> "The Significance of Tests of Petroleum Products," ASTM, Philadelphia, 1946.

<sup>1</sup> For a detailed mathematical discussion of viscosity, see BINGHAM, E. C., "Fluidity and Plasticity," McGraw-Hill Book Company, Inc., New York, 1922.

28 seconds Saybolt. Thus the instrument should be used on oils reading below 40 seconds, and never on oils below 32 seconds.

The **Saybolt Furol viscosimeter** (ASTM D88-44) is generally recommended for the determination of the viscosity of heavy fuel oils and liquid asphaltic road materials. The temperature usually employed is 122°F, although 77, 100, and 210°F may be used and, for liquid asphaltic and paving materials, also 140 and 180°F. Readings above 100 seconds are roughly one-tenth of those on the standard Saybolt instrument.

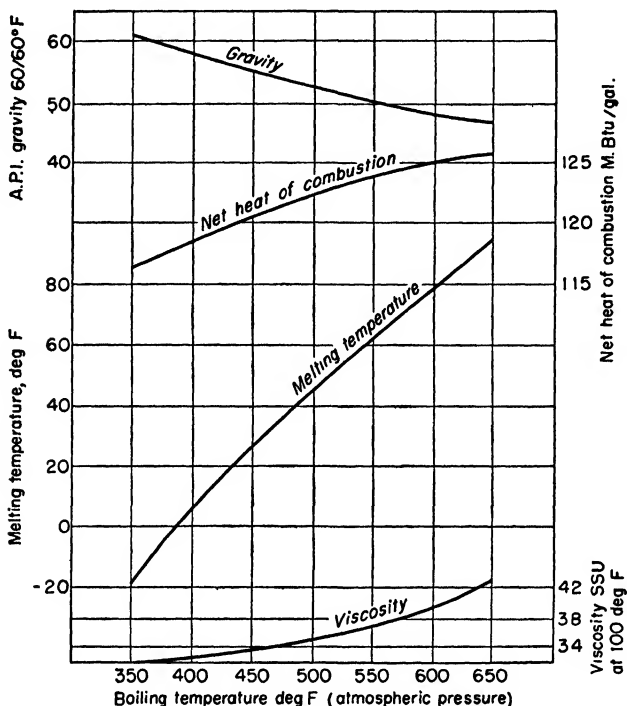


FIG. 7-7. Boiling-temperature relationships for normal paraffin hydrocarbons. (Pinker-ton, ASME, 1948.)

In the **Engler** viscosimeter, sometimes used, a different expression for viscosity is employed in that an Engler degree is the quotient of the time of outflow of 200 cc of oil divided by the corresponding time of flow of 200 cc of water. It is thus a comparison of the viscosity of the oil with that of water.

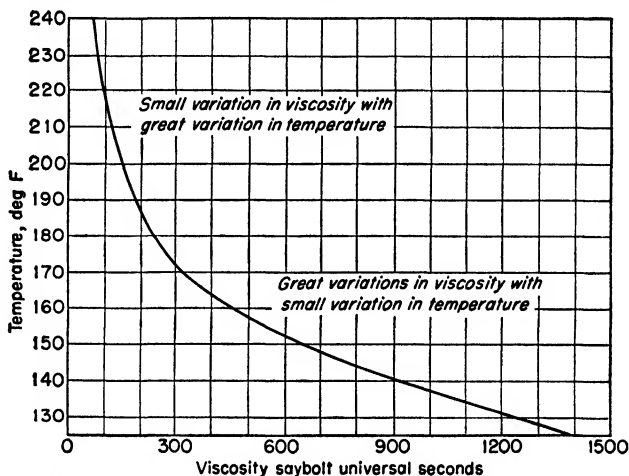
The significance of viscosity depends upon the purpose for which the oil is to be used.

For **lubricating oils**, viscosity is the most important single property, as it determines the bearing friction, heat generation, and the rate of flow under given conditions of load, speed, and bearing design. The oil should be viscous enough to maintain a fluid film between the bearing surfaces, despite the pressure tending to squeeze it out. While a reasonable factor of safety is essential, excessive viscosity means unnecessary friction and heat generation. Tests should be made at that standard temperature which most closely approximates the temperature of use. In automotive use, the viscosity of crankcase oil is one of the many factors of the ease of starting in cold weather.

For **industrial fuel oils**, viscosity is of importance mainly in determining the ease of atomization in a given type of burner, and the conditions of pressure and temperature

required to supply oil to the burner. Gravity is incorrectly used as a basis for classifying such oils with respect to viscosity.

For illuminating oils, viscosity plays only a moderate part in determining the rate of flow through a wick. The value of a test is to eliminate oils of an abnormally high viscosity which would not flow properly. There is also some indication that oils of very low viscosity will give unsteady flames. The performance of burning oils is more influenced by tendency to attack or encrust the wick than by viscosity.



Oil heated to 180°F with a variation of /or -10° shows variation of 140 sec.  
Oil heated to 220°F with a variation of /or -10° shows a viscosity variation of 35 seconds which is one-fourth of the variation at 180°

Fig. 7-8. Viscosity-temperature curve for bunker C oil. (Hauck Mfg. Co.)

For motor fuels, viscosity has little if any practical significance. The richness of mixture may be affected in some types of carburetors; in others it is negligible. Ordinary variations usually cause greater differences than changes in viscosity for fuels of proper distillation range. In general, whenever the ease or rate of circulation of oil is important, as in the case of transformer oils or oils for circulation in heat-carrying systems, viscosity becomes a factor of practical significance. This is also true of oils which must penetrate or saturate porous material. Viscosity is also important in designing pipe lines or heat exchangers.

### Gravity and Similar Weight and Volumetric Data

**Gravity.** An index of the weight of a measured volume of the product. Two scales are in general use, the specific-gravity scale and the API scale. The specific gravity of an oil is the ratio of the weights of equal volumes of oil and water at 60°F and as corrected for the buoyant effect of air. An exception is made for certain asphalts, where it is standard to use 77°F instead of 60°F. The API gravity of an oil is a mathematical function of the specific gravity as indicated by the equation

$$\text{Deg API} = \frac{141.5}{\text{sp gr } 60^{\circ}/60^{\circ}\text{F}} - 131.5$$

The figure 141.5 is termed the modulus of the API scale.

Specific gravity is generally used in continental Europe<sup>1</sup> and in many other coun-

<sup>1</sup> It is important to note that the method of computing specific gravity in Europe differs from that in use in the United States. The custom in Europe is to report the weights of equal volumes of oil and water, the former at a temperature of 15°C (59°F) and the latter at a temperature of 4°C (39.2°F). The weights are not corrected for the buoyant effect of air. When specific gravities are reported according to this system, the weight of a specified volume is directly proportionate to the specific gravity of the oil. When the specific gravities are reported according to the system in use in the United States, calculation of the exact weight of a specified volume of oil is not so simple. However, accurate and com-

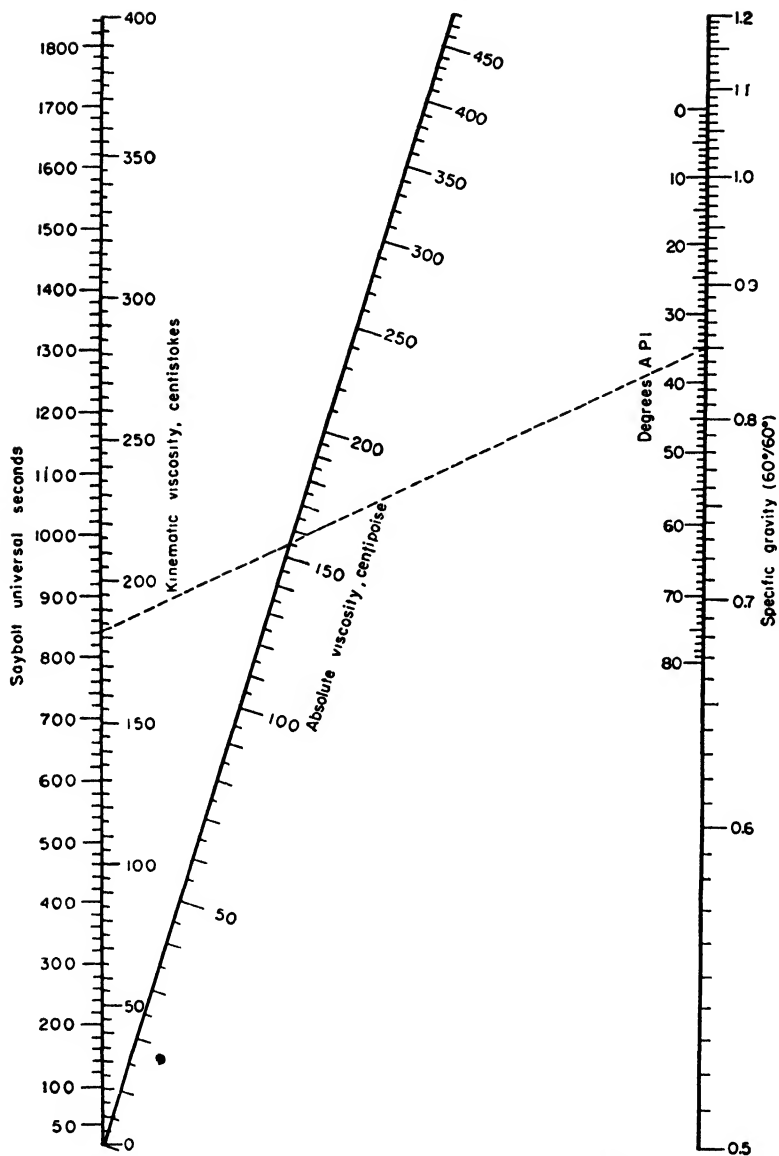


FIG. 7-9. Viscosity conversion chart based on the relations for 100°F oil temperature as given in ASTM D446-39. This relates Saybolt Universal seconds to the kinematic viscosity in centistokes. Relation between kinematic and absolute viscosities depends on the specific gravity of the oil. This may be found by comparing the weight of a volume of oil with that of an equal volume of water when both are at 60°F. It may also be found by a hydrometer graduated in API degrees.

*Example:* An oil having a specific gravity of 0.85 at 60°F has a viscosity of 840 Saybolt Universal seconds when heated up to 100°F. Find its kinematic and absolute viscosities. Lay a straightedge between the corresponding intersections on the left- and right-hand scales and find 182 centistokes kinematic viscosity, 155 centipoise absolute viscosity, and 35°API. (*John F. Hyam, Power, January, 1950.*)

tries. The API scale is generally used in the United States. The API gravity scale was formerly known as the Baumé scale, the same being changed in 1921 to avoid confusion with other Baumé scales, particularly the one based upon a modulus of 140.0. The API scale differs from this Baumé scale by amounts ranging from  $\frac{1}{10}$  deg or less for heavy fuel oils to  $\frac{3}{10}$  deg for gasoline.

Solid and plastic materials such as paraffin wax and petrolatum are usually sold on a weight instead of a gravity basis, so that tests for their gravity are relatively unimportant.

As petroleum products are frequently sold on a basis of volumes delivered, corrected to 60°F, the gravity and correction tables for converting are of considerable importance. Gravity is of little significance as an index of the quality or usefulness of a finished produce, and its use in specifications is to be avoided.

**Reduction of Observed Specific Gravities to Specific Gravities at 60°/60°F.** Table 7-12 shows the specific gravity at 60°/60°F of oils having, at the observed temperatures, the specific gravity indicated. (For example, if the observed specific gravity at 95°F is 0.750, the specific gravity at 60°/60°F will be 0.7649.) As was the case with other tables from "National Standard Petroleum Oil Tables," space did not permit the reproduction of all values originally shown; intermediate values can be interpolated.

The headings "Observed specific gravity" and "Observed temperature" signify the true indication of the hydrometer and the true temperature of the oil; *i.e.*, the observed readings corrected for instrumental errors. (This table is computed so as to

**Table 7-10. Degrees API, Pounds per Gallon, and Gallons per Pound, Corresponding to the Designated Specific Gravities<sup>1</sup>**

Sp gr at 60°/60°F	Deg API	Lb/gal	Gal/lb	Sp gr at 60°/60°F	Deg API	Lb/gal	Gal/lb
0.60	104.33	4.993	0.2003	0.81	43.19	6.744	0.1483
0.61	100.47	5.076	0.1970	0.82	41.06	6.827	0.1465
0.62	96.73	5.160	0.1938	0.83	38.98	6.911	0.1447
0.63	93.10	5.243	0.1907	0.84	36.95	6.994	0.1430
0.64	89.59	5.326	0.1877	0.85	34.97	7.078	0.1413
0.65	86.19	5.410	0.1848	0.86	33.03	7.161	0.1396
0.66	82.89	5.493	0.1820	0.87	31.14	7.244	0.1380
0.67	79.69	5.577	0.1793	0.88	29.30	7.328	0.1365
0.68	76.59	5.660	0.1767	0.89	27.49	7.411	0.1349
0.69	73.57	5.743	0.1741	0.90	25.72	7.494	0.1334
0.70	70.64	5.827	0.1716	0.91	23.99	7.578	0.1320
0.71	67.80	5.910	0.1692	0.92	22.30	7.661	0.1305
0.72	65.03	5.994	0.1668	0.93	20.65	7.745	0.1291
0.73	62.34	6.077	0.1646	0.94	19.03	7.828	0.1278
0.74	59.72	6.160	0.1623	0.95	17.45	7.911	0.1264
0.75	57.17	6.244	0.1602	0.96	15.90	7.995	0.1251
0.76	54.68	6.327	0.1580	0.97	14.38	8.078	0.1238
0.77	52.27	6.410	0.1560	0.98	12.89	8.162	0.1225
0.78	49.91	6.494	0.1540	0.99	11.43	8.245	0.1213
0.79	47.61	6.577	0.1520	1.00	10.00	8.328	0.1201
0.80	45.38	6.661	0.1501	1.01	8.60	8.412	0.1189
				1.02	7.23	8.495	0.1177

<sup>1</sup> Abridged from "National Standard Petroleum Oil Tables," NBS Circ. C-410, 1936.

prehensive tables published by the National Bureau of Standards simplify this conversion. ("National Standard Petroleum Oil Tables," NBS Cir. C410, Government Printing Office, Washington, D.C., 1936.)



Table 7-11. Degrees API, Pounds per Gallon, and Gallons per Pound, Corresponding to the Designated Degrees API<sup>1</sup>

Deg API	Sp gr at 60°/60°F	Lb/gal	Gal/lb	Deg API	Sp gr at 60°/60°F	Lb/gal	Gal/lb
0	1.0760	8.962	0.1116	50	0.7796	6.490	0.1541
1	1.0679	8.895	0.1124	51	0.7753	6.455	0.1459
2	1.0599	8.828	0.1133	52	0.7711	6.420	0.1558
3	1.0520	8.762	0.1141	53	0.7669	6.385	0.1566
4	1.0443	8.698	0.1150	54	0.7628	6.350	0.1575
5	1.0366	8.634	0.1158	55	0.7587	6.316	0.1583
6	1.0291	8.571	0.1167	56	0.7547	6.283	0.1592
7	1.0217	8.509	0.1175	57	0.7507	6.249	0.1600
8	1.0143	8.448	0.1184	58	0.7467	6.216	0.1609
9	1.0071	8.388	0.1192	59	0.7428	6.184	0.1617
10	1.0000	8.328	0.1202	60	0.7389	6.151	0.1626
11	0.9930	8.270	0.1209	61	0.7351	6.119	0.1634
12	0.9861	8.212	0.1218	62	0.7313	6.087	0.1643
13	0.9792	8.155	0.1226	63	0.7275	6.056	0.1651
14	0.9725	8.099	0.1235	64	0.7238	6.025	0.1660
15	0.9659	8.044	0.1243	65	0.7201	5.994	0.1668
16	0.9593	7.989	0.1252	66	0.7165	5.964	0.1677
17	0.9529	7.935	0.1260	67	0.7128	5.934	0.1685
18	0.9465	7.882	0.1269	68	0.7093	5.904	0.1694
19	0.9402	7.830	0.1277	69	0.7057	5.874	0.1702
20	0.9340	7.778	0.1286	70	0.7022	5.845	0.1711
21	0.9279	7.729	0.1294	71	0.6988	5.817	0.1719
22	0.9218	7.676	0.1303	72	0.6953	5.788	0.1728
23	0.9159	7.627	0.1311	73	0.6919	5.759	0.1736
24	0.9100	7.578	0.1320	74	0.6886	5.731	0.1745
25	0.9042	7.529	0.1328	75	0.6852	5.703	0.1753
26	0.8984	7.481	0.1337	76	0.6819	5.676	0.1762
27	0.8927	7.434	0.1345	77	0.6787	5.649	0.1770
28	0.8871	7.387	0.1354	78	0.6754	5.622	0.1779
29	0.8816	7.341	0.1362	79	0.6722	5.595	0.1787
30	0.8762	7.296	0.1371	80	0.6690	5.568	0.1796
31	0.8708	7.251	0.1379	81	0.6659	5.542	0.1804
32	0.8654	7.206	0.1388	82	0.6628	5.516	0.1813
33	0.8602	7.163	0.1396	83	0.6597	5.491	0.1821
34	0.8550	7.119	0.1405	84	0.6566	5.465	0.1830
35	0.8498	7.076	0.1413	85	0.6536	5.440	0.1838
36	0.8448	7.034	0.1422	86	0.6506	5.415	0.1847
37	0.8398	6.993	0.1430	87	0.6476	5.390	0.1855
38	0.8348	6.951	0.1439	88	0.6446	5.365	0.1864
39	0.8299	6.910	0.1447	89	0.6417	5.341	0.1872
40	0.8251	6.870	0.1456	90	0.6388	5.316	0.1881
41	0.8203	6.830	0.1464	91	0.6360	5.293	0.1889
42	0.8155	6.790	0.1473	92	0.6331	5.269	0.1898
43	0.8109	6.752	0.1481	93	0.6303	5.246	0.1906
44	0.8063	6.713	0.1490	94	0.6275	5.222	0.1915
45	0.8017	6.675	0.1498	95	0.6247	5.199	0.1924
46	0.7972	6.637	0.1507	96	0.6220	5.176	0.1932
47	0.7927	6.600	0.1515	97	0.6193	5.154	0.1940
48	0.7883	6.563	0.1524	98	0.6166	5.131	0.1949
49	0.7839	6.526	0.1528	99	0.6139	5.109	0.1957
				100	0.6112	5.086	0.1966

<sup>1</sup> Abridged from "National Standard Petroleum Oil Tables," NBS Circ. C-410, 1936.

Table 7-12. Reduction of Observed Specific Gravities to Specific Gravities at 60°/60°F<sup>1</sup>

Observed temp, deg F	Observed specific gravity								
	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	0.999
	Corresponding specific gravities at 60°/60°F								
0	0.5634	0.6172	0.6704	0.7224	0.7749	0.8271	0.8780	0.9285	0.9776
5	0.5667	0.6201	0.6729	0.7248	0.7772	0.8293	0.8801	0.9303	0.9793
10	0.5699	0.6230	0.6754	0.7272	0.7793	0.8312	0.8819	0.9321	0.9811
15	0.5730	0.6258	0.6779	0.7295	0.7816	0.8331	0.8838	0.9338	0.9830
20	0.5762	0.6286	0.6804	0.7319	0.7836	0.8350	0.8856	0.9356	0.9847
25	0.5792	0.6314	0.6829	0.7342	0.7858	0.8369	0.8874	0.9374	0.9865
30	0.5822	0.6342	0.6854	0.7365	0.7879	0.8389	0.8893	0.9393	0.9884
35	0.5854	0.6369	0.6879	0.7389	0.7899	0.8407	0.8911	0.9411	0.9902
40	0.5884	0.6395	0.6903	0.7411	0.7919	0.8426	0.8929	0.9429	0.9920
45	0.5913	0.6422	0.6928	0.7434	0.7940	0.8444	0.8947	0.9447	0.9938
50	0.5942	0.6448	0.6952	0.7456	0.7960	0.8463	0.8964	0.9465	0.9955
55	0.5971	0.6475	0.6976	0.7479	0.7980	0.8481	0.8982	0.9482	0.9972
60	0.6000	0.6500	0.7000	0.7500	0.8000	0.8500	0.9000	0.9500	0.9990
65	0.6029	0.6526	0.7024	0.7522	0.8020	0.8518	0.9018	0.9518	1.0008
70	0.6057	0.6551	0.7048	0.7543	0.8039	0.8537	0.9036	0.9535	1.0025
75	0.6085	0.6576	0.7071	0.7565	0.8059	0.8555	0.9054	0.9553	1.0043
80	0.6112	0.6602	0.7094	0.7586	0.8078	0.8573	0.9072	0.9570	1.0060
85	0.6140	0.6627	0.7118	0.7607	0.8098	0.8592	0.9089	0.9588	1.0077
90	0.6166	0.6652	0.7141	0.7628	0.8116	0.8610	0.9106	0.9605	1.0094
95	.	.	0.7164	0.7649	0.8134	0.8627	0.9124	0.9622	1.0112
100	...	.	0.7188	0.7670	0.8153	0.8644	0.9141	0.9639	1.0129
105	.	...	0.7209	0.7690	0.8172	0.8663	0.9159	0.9656	1.0146
110	...	...	0.7232	0.7710	0.8191	0.8680	0.9176	0.9673	1.0163
115	.	...	0.7254	0.7729	0.8209	0.8698	0.9193	0.9690	1.0180
120	.	...	0.7275	0.7749	0.8227	0.8715	0.9210	0.9707	1.0197
125	.	...	0.7297	0.7769	0.8245	0.8733	0.9227	0.9725	1.0214
130	.	...	0.7319	0.7789	0.8263	0.8750	0.9245	0.9743	1.0231
135	...	...	...	...	0.8281	0.8767	0.9261	0.9759	1.0247
140	...	...	...	...	0.8299	0.8786	0.9279	0.9775	1.0263
145	.	...	...	...	0.8318	0.8802	0.9295	0.9792	1.0280
150	...	...	...	...	0.8335	0.8818	0.9312	0.9809	1.0297
155	...	...	...	...	0.8353	0.8835	0.9328	0.9825	1.0314
160	...	...	...	...	0.8370	0.8853	0.9346	0.9843	1.0330
165	...	...	...	...	0.8388	0.8871	0.9363	0.9859	1.0345
170	...	...	...	...	0.8406	0.8887	0.9380	0.9875	1.0361
175	...	...	...	...	0.8423	0.8905	0.9396	0.9891	1.0377
180	...	...	...	...	0.8441	0.8921	0.9413	0.9906	1.0393
185	...	...	...	...	0.8458	0.8938	0.9429	0.9922	1.0409
190	...	...	...	...	0.8476	0.8955	0.9445	0.9938	1.0425
195	...	...	...	...	0.8493	0.8971	0.9462	0.9954	1.0441

<sup>1</sup> "National Standard Petroleum Oil Tables," NBS Circ. C-410, 1936.

take into account the thermal expansion of the glass of which the hydrometer is made.)

**Reduction of Observed Degrees API to Degrees API at 60°F.** Table 7-13 shows the degrees API at 60°F of oils having, at the observed temperatures, the degrees API indicated. (For example, if the observed degrees API at 80°F is 20, the degrees API at 60°F will be 18.9.) Intermediate values can be interpolated. The headings

"Observed degrees API" and "Observed temperature" signify the true indication of the hydrometer and the true temperature of the oils; *i.e.*, the observed readings corrected for instrumental errors. (This table is so computed as to take into account the thermal expansion of the glass of which the hydrometer is made.)

**Volume at 60°F Occupied by Unit Volume at Indicated Temperature.** Table 7-14 shows the volume occupied at 60°F by a quantity of oil at any API gravity at 60°F occupying unit volume at the indicated temperatures. (For example, if at 60°F the

**Table 7-13. Reduction of Observed Degrees API to Degrees API at 60°F<sup>1</sup>**

Observed temp, deg F	Observed deg API															
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
	Corresponding deg API at 60°F															
0	2.5	7.8	13.1	18.3	23.6	28.9	34.2	39.6	45.1	50.7	56.3	61.9	67.6	73.2	78.8	84.6
5	2.3	7.6	12.8	18.0	23.3	28.5	33.8	39.2	44.6	50.1	55.7	61.3	66.9	72.4	78.1	83.7
10	2.1	7.3	12.6	17.8	23.0	28.2	33.4	38.8	44.1	49.6	55.2	60.7	66.2	71.7	77.3	82.9
15	1.9	7.1	12.3	17.5	22.7	27.9	33.1	38.4	43.7	49.1	54.6	60.1	65.5	71.0	76.5	82.0
20	1.7	6.9	12.0	17.2	22.4	27.5	32.7	38.0	43.3	48.7	54.1	59.5	64.9	70.3	75.8	81.2
25	1.5	6.6	11.8	16.9	22.1	27.2	32.4	37.6	42.8	48.2	53.5	58.9	64.2	69.6	75.0	80.4
30	1.2	6.4	11.5	16.6	21.7	26.9	32.0	37.2	42.4	47.7	53.0	58.3	63.6	68.9	74.3	79.6
35	1.0	6.1	11.3	16.4	21.4	26.6	31.7	36.8	42.0	47.2	52.5	57.7	63.0	68.2	73.5	78.8
40	0.8	5.9	11.0	16.1	21.2	26.2	31.3	36.5	41.6	46.8	52.0	57.2	62.4	67.6	72.8	78.0
45	0.6	5.7	10.7	15.8	20.9	25.9	31.0	36.1	41.2	46.3	51.5	56.6	61.8	66.9	72.1	77.2
50	0.4	5.5	10.5	15.5	20.6	25.6	30.7	35.7	40.8	45.9	51.0	56.1	61.2	66.3	71.4	76.5
55	0.2	5.2	10.3	15.3	20.3	25.3	30.3	35.4	40.4	45.4	50.5	55.5	60.6	65.6	70.7	75.7
60	0.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0
65	..	4.8	9.8	14.7	19.7	24.7	29.7	34.7	39.6	44.6	49.5	54.5	59.4	64.4	69.3	74.3
70	...	4.6	9.5	14.5	19.4	24.4	29.3	34.3	39.2	44.1	49.0	54.0	58.9	63.8	68.6	73.6
75	...	4.3	9.3	14.2	19.1	24.1	29.0	33.9	38.8	43.7	48.6	53.5	58.3	63.1	68.0	72.9
80	...	4.1	9.0	13.9	18.9	23.8	28.7	33.6	38.4	43.3	48.1	53.0	57.8	62.6	67.4	72.2
85	...	3.9	8.8	13.7	18.6	23.5	28.4	33.2	38.1	42.9	47.7	52.5	57.2	61.9	66.7	72.4
90	...	3.7	8.5	13.4	18.3	23.2	28.0	32.9	37.7	42.5	47.2	52.0	56.7	61.4	66.1	70.8
95	...	3.4	8.3	13.2	18.0	22.9	27.7	32.6	37.3	42.1	46.8	51.5	56.1	60.8		
100	...	3.2	8.1	12.9	17.8	22.6	27.4	32.2	37.0	41.7	46.4	51.0	55.6	60.2		
105	...	3.0	7.8	12.7	17.5	22.3	27.1	31.9	36.6	41.3	46.0	50.5	55.1	59.6		
110	...	2.8	7.6	12.4	17.2	22.0	26.8	31.5	36.2	40.9	45.5	50.1	54.6	59.1		
115	...	2.6	7.4	12.2	17.0	21.7	26.5	31.2	35.9	40.5	45.1	49.6	54.1	58.5		
120	...	2.4	7.1	11.9	16.7	21.4	26.2	30.9	35.5	40.2	44.7	49.2	53.6	58.0		
125	...	2.1	6.9	11.7	16.4	21.2	25.9	30.6	35.2	39.8	44.3	48.7	53.1	57.5		
130	...	1.9	6.7	11.4	16.2	20.9	25.6	30.2	34.8	39.4						
135	...	1.7	6.4	11.2	15.9	20.6	25.3	29.9	34.5	39.0						
140	...	1.5	6.2	10.9	15.6	20.3	25.0	29.6	34.2	38.7						
145	...	1.3	6.0	10.7	15.4	20.0	24.7	29.3	33.8	38.3						
150	...	1.1	5.8	10.5	15.1	19.8	24.4	29.0	33.5	37.9						
155	...	0.9	5.6	10.2	14.9	19.5	24.1	28.7								
160	...	0.7	5.3	10.0	14.6	19.2	23.8	28.4								
165	...	0.5	5.1	9.8	14.4	18.9	23.5	28.0								
170	...	0.3	4.9	9.5	14.1	18.7	23.2	27.7								
175	...	0.1	4.7	9.3	13.9	18.4	22.9	27.4								
180	...	..	4.5	9.1	13.6	18.2	22.7	27.1								
185	...	..	4.3	8.9	13.4	17.9	22.4	26.8								
190	...	..	4.1	8.7	13.2	17.7	22.1	26.5								
195	...	..	3.9	8.5	12.9	17.4	21.8	26.3								

<sup>1</sup> "National Standard Petroleum Oil Tables," *NBS Circ. C-410*, 1936.

**Table 7-14. Volume at 60°F Occupied by Unit Volume at Indicated Temperature<sup>1</sup>**  
(Table for correcting oil volumes as measured, to true volume at standard 60°F temperature)

Observed temp, deg F	Deg API at 60°F											
	10	20	25	30	35	40	45	50	55	60	70	80
	Volume at 60°F occupied by unit volume at indicated temperature											
0	1.0223	1.0239	1.0247	1.0256	1.0269	1.0284	1.0301	1.0324	1.0347	1.0370	1.0411	1.0451
5	1.0204	1.0219	1.0226	1.0234	1.0247	1.0261	1.0276	1.0297	1.0318	1.0339	1.0377	1.0414
10	1.0185	1.0199	1.0205	1.0213	1.0224	1.0237	1.0251	1.0270	1.0290	1.0309	1.0343	1.0377
15	1.0166	1.0179	1.0184	1.0192	1.0202	1.0213	1.0226	1.0243	1.0261	1.0278	1.0309	1.0340
20	1.0148	1.0159	1.0164	1.0170	1.0179	1.0189	1.0201	1.0216	1.0232	1.0247	1.0275	1.0302
25	1.0129	1.0139	1.0143	1.0149	1.0157	1.0166	1.0176	1.0189	1.0203	1.0217	1.0241	1.0265
30	1.0111	1.0119	1.0123	1.0128	1.0134	1.0142	1.0151	1.0162	1.0174	1.0186	1.0207	1.0227
35	1.0092	1.0099	1.0102	1.0106	1.0112	1.0119	1.0126	1.0135	1.0145	1.0155	1.0172	1.0190
40	1.0073	1.0079	1.0082	1.0085	1.0090	1.0095	1.0100	1.0108	1.0116	1.0124	1.0138	1.0152
45	1.0055	1.0059	1.0061	1.0064	1.0067	1.0071	1.0075	1.0081	1.0087	1.0093	1.0104	1.0114
50	1.0037	1.0039	1.0041	1.0042	1.0045	1.0047	1.0050	1.0054	1.0058	1.0062	1.0069	1.0076
55	1.0018	1.0020	1.0020	1.0021	1.0022	1.0024	1.0025	1.0027	1.0029	1.0031	1.0035	1.0038
60	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
65	0.9982	0.9980	0.9980	0.9979	0.9978	0.9976	0.9975	0.9973	0.9971	0.9969	0.9965	0.9962
70	0.9964	0.9961	0.9959	0.9958	0.9955	0.9953	0.9950	0.9946	0.9942	0.9938	0.9931	0.9924
75	0.9946	0.9941	0.9939	0.9937	0.9933	0.9929	0.9924	0.9919	0.9913	0.9907	0.9896	0.9885
80	0.9928	0.9922	0.9919	0.9915	0.9911	0.9905	0.9899	0.9891	0.9884	0.9876	0.9861	0.9847
85	0.9910	0.9902	0.9899	0.9894	0.9888	0.9881	0.9874	0.9864	0.9854	0.9844	0.9826	0.9809
90	0.9892	0.9983	0.9878	0.9873	0.9866	0.9858	0.9849	0.9837	0.9825	0.9813	0.9792	0.9770
95	0.9874	0.9863	0.9857	0.9852	0.9844	0.9834	0.9824	0.9810	0.9796	0.9782		
100	0.9856	0.9844	0.9837	0.9831	0.9822	0.9811	0.9799	0.9783	0.9767	0.9751		
105	0.9838	0.9825	0.9816	0.9810	0.9800	0.9787	0.9773	0.9756	0.9737	0.9720		
110	0.9820	0.9806	0.9798	0.9789	0.9777	0.9763	0.9748	0.9729	0.9708	0.9689		
115	0.9802	0.9786	0.9778	0.9768	0.9755	0.9739	0.9723	0.9702	0.9679	0.9657		
120	0.9785	0.9767	0.9758	0.9747	0.9733	0.9716	0.9698	0.9674	0.9650	0.9626		
125	0.9767	0.9748	0.9738	0.9726	0.9711	0.9692	0.9673	0.9647	0.9620	0.9595		
130	0.9750	0.9729	0.9718	0.9705	0.9689	0.9669	0.9647					
135	0.9732	0.9710	0.9699	0.9684	0.9667	0.9645	0.9622					
140	0.9715	0.9691	0.9679	0.9664	0.9645	0.9622	0.9597					
145	0.9698	0.9672	0.9659	0.9643	0.9623	0.9598	0.9572					
150	0.9680	0.9653	0.9639	0.9622	0.9601	0.9574	0.9547					
155	0.9663	0.9634	0.9620	0.9601	0.9579							
160	0.9646	0.9615	0.9600	0.9580	0.9557							
165	0.9629	0.9597	0.9580	0.9560	0.9535							
170	0.9612	0.9578	0.9560	0.9539	0.9513							
175	0.9595	0.9559	0.9541	0.9518	0.9491							
180	0.9578	0.9540	0.9521	0.9497	0.9469							
185	0.9561	0.9522	0.9502	0.9477	0.9447							
190	0.9544	0.9503	0.9482	0.9456	0.9425							
195	0.9527	0.9485	0.9463	0.9436	0.9403							

<sup>1</sup> "National Standard Petroleum Oil Tables," NBS Circ. C-410, 1936.

API gravity of the oil is 20, 1 gal of this oil measured at 105°F will have a volume of 0.9825 gal at 60°F.) Intermediate values can be interpolated.

The values given in the body of the table are in the form of "multipliers"; i.e., the volume of the oil at the indicated temperature and degrees API multiplied by the corresponding factor in the table equals the volume at 60°F. (For example, if the API gravity of an oil at 60°F equals 20 and the volume at 105°F equals 5,000 gal, then the volume at 60°F equals 5,000 × 0.9825, or 4,912.5 gal.)

This table can also be used to calculate the percentage change of volume to reduce to 60°F. The percentage factor is 100 times the difference between the tabulated value and unity. [For example, in the case given above, the percentage factor is  $100 \times (1.0000 - 0.9825)$  or 1.75; *i.e.*, any volume of oil of 20° API at 60°F measured at 105°F will decrease in volume by 1.75 per cent on being reduced to a temperature of 60°F.] For observed temperatures below 60°F, the volume correction should be added to the measured volumes; for temperatures above 60°F, it should be subtracted.

### Sulphur Derivatives<sup>1</sup>

Sulphur usually exists as mercaptans, sulphides, and disulphides. **Mercaptans** may be visualized as hydrocarbons in which a sulphur atom has been inserted between a carbon atom and its associated hydrogen atom; weakly acidic, this type is most characteristic from a standpoint of its odor. In **sulphides** a sulphur atom has been inserted between two saturated carbon atoms, such as are found in the paraffin series; neutral with respect to acid, sulphides have no characteristic or objectionable odor. **Disulphides** are analogous to the sulphides except that two sulphur atoms are imposed between two saturated carbon atoms; these disulphides are produced in treating to reduce objectionable mercaptans to the less objectionable disulphides.

Combustion of sulphur compounds gives oxides of sulphur which appear in the product gases. These oxides may take up water to form the well-known sulphur acids.

**Total Sulphur or Sulphur Content.** In commercial testing it is customary to determine the total amount of sulphur without attempting separation into the various classes of compounds. The doctor test and corrosion test give indications of certain particular types of compounds. The quantitative determination of sulphur consists of a complete oxidation of the material and an analysis of the products.

The significance of total sulphur content varies greatly with the product and the

**Table 7-15. Degrees API (Modulus 141.5) Corresponding to Degrees Baumé (Modulus 140)<sup>1</sup>**

Deg Baumé	Deg API	Deg Baumé	Deg API	Deg Baumé	Deg API	Deg Baumé	Deg API
10	10 00	30	30 21	50	50 43	70	70 64
11	11 01	31	31 22	51	51 44	71	71 65
12	12 02	32	32 24	52	52 45	72	72 66
13	13 03	33	33 25	53	53 46	73	73 68
14	14 04	34	34 26	54	54 47	74	74 69
15	15 05	35	35 27	55	55 48	75	75 70
16	16 06	36	36 28	56	56 49	76	76 71
17	17 08	37	37 29	57	57 50	77	77 72
18	18 09	38	38 30	58	58 51	78	78 73
19	19 10	39	39 31	59	59 52	79	79 74
20	20 11	40	40 32	60	60 54	80	80 75
21	21 12	41	41 33	61	61 55	81	81 76
22	22 13	42	42 34	62	62 56	82	82 77
23	23 14	43	43 35	63	63 57	83	83 78
24	24 15	44	44 36	64	64 58	84	84 79
25	25 16	45	45 38	65	65 59	85	85 80
26	26 17	46	46 39	66	66 60	86	86 81
27	27 18	47	47 40	67	67 61	87	87 82
28	28 19	48	48 41	68	68 62	88	88 84
29	29 20	49	49 42	69	69 63	89	89 85

<sup>1</sup> National Standard Petroleum Oil Tables, *NBS Circ. C-410*, 1936

<sup>1</sup> PINKERTON, R. D., "Diesel Fuel Oils," p. 33, ASME, 1948.

uses to which it is put. In general, total sulphur is important only when the material is to be burned under conditions which make undesirable the presence of much sulphur dioxide in the products of combustion; otherwise only the corrosive forms of sulphur are undesirable, and these should preferably be detected by appropriate corrosion tests (see Corrosion Tests). More specifically, the following effects of sulphur are significant:

**Motor Fuels.** While total sulphur, as distinct from corrosive sulphur, has no significance in connection with the induction system of an engine, it may cause trouble, particularly in the winter, because a small portion of the products of combustion may find its way into the crankcase, and a portion may also remain in the cylinders when the engine is stopped. If the fuel contains much sulphur, and water is present, a dilute solution of sulphurous and sulphuric acid is formed, which may cause serious corrosion. This trouble is characteristic only of winter operation in engines which, because of their design or method of operation, run rather cold or are so poorly ventilated that they accumulate quantities of water.

**Burning Oils.** Any oil for lamps or stoves indoors obviously should have a fairly low sulphur content. The presence of considerable quantities of sulphur also appears to injure the burning qualities of an oil in a wick burner.

**Fuel Oils.** The importance of the total sulphur content of a fuel oil is frequently overestimated. The sulphur compounds are readily combustible and have a high heat value; and, in a properly arranged household or industrial furnace, they are neither noticeable nor harmful, except in certain metallurgical operations and in a few cases where the use of highly efficient economizers cools the flue gases to temperatures which permit the condensation of water and sulphurous acid on metal surfaces, with resulting corrosion. Most of the lighter or distillate fuel oils contain less sulphur per unit heating value than does coal.

**Lubricating Oils.** The total sulphur content of ordinary lubricating oils is of no known significance. The quantity of oil actually burned in an automobile engine seldom exceeds 1 per cent of the gasoline burned, and therefore its products of combustion can have no appreciable effect on crankcase corrosion.

In thread-cutting oils, there is a popular belief that high-sulphur oil makes possible more rapid cutting and smoother work. Recently, oils have appeared which contained added sulphur and or sulphur compounds. They are intended for use under extreme pressure conditions especially in hypoid gears and certain types of worm gears.

**General.** Sulphur dioxide itself is not a corrosive agent except when dissolved in water, and the temperatures in flue-gas systems are seldom low enough to permit this. The importance of the sulphur content of any product can be estimated only after careful consideration of the conditions of use.

### Thermal Values and Other Thermal Properties

**Thermal Value of Fuel Oil.** The thermal (calorific) value of a fuel is the amount of heat generated as a result of its complete combustion. The thermal value of any given type of fuel oil varies in linear relationship with the API gravity of the product. This has led to the development of numerous formulas for calculating thermal value, most of which are in the general form

$$\text{Btu/lb} = A + (B \times \text{API gravity})$$

The oldest, and perhaps best known, of these is that of Sherman and Kropff.<sup>1</sup> Their original equation was as follows:

$$\text{Btu/lb} = 18,650 + (40 \times \text{gravity, deg Baumé} - 10)$$

This can be expressed more conveniently in the following form, which disregards the possible small difference between the Baumé scale and the present standard API gravity scale:

$$\text{Btu/lb} = 18,250 + (40 \times \text{API gravity})$$

The Sherman and Kropff equation, though still widely used, is generally recognized

<sup>1</sup> SHERMAN, H. C., and A. C. KROFF, *The Calorific Power of Petroleum Oils and the Relation of Density to Calorific Power*, *J. ACS*, vol. 30, p. 1626, 1908.

to be unsuitable for present-day heavy fuel oils. Faragher, Morrell, and Essex<sup>1</sup> have reviewed this field and have proposed the following equation for cracked fuel oils:

$$\text{Btu/lb} = 17,645 + (54 \times \text{API gravity})$$

This is in fairly close agreement with the following equation proposed in an unpublished report of the Naval Boiler Laboratory, Navy Yard, Philadelphia (Lybrand P. Smith, May, 1933):

$$\text{Btu/lb} = 17,687 + (57.9 \times \text{API gravity})$$

The National Bureau of Standards (in *Thermal Properties of Petroleum Products, Miscellaneous Publication 97*, 1933) publishes tables giving the thermal values of various oils in terms of gravity. \* These are shown herein as Tables 7-16, 7-17, and 7-18. The basis for the Bureau of Standards calculations is as follows:

**Total Heat of Combustion at Constant Volume.**

$$Q_V = 12,400 - (2,100 \times \text{specific gravity})^2$$

where  $Q_V$  is expressed in calories per gram

In most processes of combustion the water vapor formed is not condensed under useful conditions; the net heat of combustion at constant pressure ( $Q_P$ ) is thus the more significant quantity in making comparisons of fuels and in calculating the efficiency of heating appliances.

Values for the net heat of combustion, in calories per gram, were calculated from those for total heat, as obtained in a bomb calorimeter, by the following formula:

$$Q_P = Q_V - (50.45 \times \text{per cent H})$$

Values in calories per gram multiplied by 1.8 give Btu per pound, and the latter, multiplied by pounds per gallon, yield Btu per gallon.

As a rough approximation, it may be stated that, for oils having API gravities between 10 and 20, the net thermal value is from 1,000 to 1,100 Btu lower than the gross thermal value.

Faragher, Morrell, and Essex have shown that the so-called "sediment" in fuel oil has a slightly lower thermal value than the oil itself but that the error introduced by disregarding this factor is negligible. Moisture content also obviously affects the thermal content but can ordinarily be disregarded, as the correction is of the order of 1 Btu for each 0.1 per cent water present in the fuel oil.

Average values for percentages of hydrogen in oils at various specific gravities may be obtained from the relation

$$\text{Per cent H} = 26 - (15 \times \text{specific gravity})$$

It will be noted that the hydrogen content decreases as the gravity becomes heavier.

**Heating Values for Other Petroleum Products.** The Bureau of Standards notes that the values given in Table 7-17 are probably too high by 1 or 2 per cent for products containing unusually large amounts of aromatic hydrocarbons, e.g., "vapor-phase-cracked" gasoline.

Table 7-17 is accurate within about 0.5 per cent for such other liquid hydrocarbons as propane, isobutane, *n*-pentane, isopentane, *n*-heptane, *n*-octane, *n*-decane, cyclopentane, cyclohexane, cycloheptane, methylcyclohexane, and diethylcyclohexane.

<sup>1</sup> FARAGHER, W. F., J. C. MORRELL, and J. L. ESSEX, Relationship between Calorific Value and Other Characteristics of Residual Fuel Oils and Cracked Residuum Oils, *Ind. Eng. Chem.*, vol. 21, p. 933, 1929.

Table 7-16. Heats of Combustion of Crude Oils, Fuel Oils, and Kerosene<sup>1</sup>

Gravity		Density	Total heat of combustion at constant volume, $Q_v$			Net heat of combustion at constant pressure, $Q_p$		
Deg API at 60°F	Sp gr at 60°/60°F	Lb/gal	Cal/g	Btu/lb	Btu/gal	Cal/g	Btu/lb	Btu/gal
10	1.0000	8.337	10,300	18,540	154,600	9,740	17,540	146,200
11	0.9930	8.279	10,330	18,590	153,900	9,770	17,580	145,600
12	0.9861	8.221	10,360	18,640	153,300	9,790	17,620	144,900
13	0.9792	8.164	10,390	18,690	152,600	9,810	17,670	144,200
14	0.9725	8.108	10,410	18,740	152,000	9,840	17,710	143,600
15	0.9659	8.053	10,440	18,790	151,300	9,860	17,750	142,900
16	0.9593	7.998	10,470	18,840	150,700	9,880	17,790	142,300
17	0.9529	7.944	10,490	18,890	150,000	9,900	17,820	141,600
18	0.9465	7.891	10,520	18,930	149,400	9,920	17,860	140,900
19	0.9402	7.839	10,540	18,980	148,800	9,940	17,900	140,300
20	0.9340	7.787	10,570	19,020	148,100	9,960	17,930	139,600
21	0.9279	7.736	10,590	19,060	147,500	9,980	17,960	139,000
22	0.9218	7.686	10,620	19,110	146,800	10,000	18,000	138,300
23	0.9159	7.636	10,640	19,150	146,200	10,020	18,030	137,700
24	0.9100	7.587	10,660	19,190	145,600	10,040	18,070	137,100
25	0.9042	7.538	10,680	19,230	145,000	10,050	18,100	136,400
26	0.8984	7.490	10,710	19,270	144,300	10,070	18,130	135,800
27	0.8927	7.443	10,730	19,310	143,700	10,090	18,160	135,200
28	0.8871	7.396	10,750	19,350	143,100	10,110	18,190	134,600
29	0.8816	7.350	10,770	19,380	142,500	10,120	18,220	133,900
30	0.8762	7.305	10,790	19,420	141,800	10,140	18,250	133,300
31	0.8708	7.260	10,810	19,450	141,200	10,150	18,280	132,700
32	0.8654	7.215	10,830	19,490	140,600	10,170	18,310	132,100
33	0.8602	7.171	10,850	19,520	140,000	10,180	18,330	131,500
34	0.8550	7.128	10,860	19,560	139,400	10,200	18,360	130,900
35	0.8498	7.085	10,880	19,590	138,800	10,210	18,390	130,300
36	0.8448	7.043	10,900	19,620	138,200	10,230	18,410	129,700
37	0.8398	7.001	10,920	19,650	137,600	10,240	18,430	129,100
38	0.8348	6.960	10,940	19,680	137,000	10,260	18,460	128,500
39	0.8299	6.920	10,950	19,720	136,400	10,270	18,480	127,900
40	0.8251	6.879	10,970	19,790	135,800	10,280	18,510	127,300
41	0.8203	6.839	10,990	19,780	135,200	10,300	18,530	126,700
42	0.8155	6.799	11,000	19,810	134,700	10,310	18,560	126,200
43	0.8109	6.760	11,020	19,830	134,100	10,320	18,580	125,600
44	0.8063	6.722	11,030	19,860	133,500	10,330	18,600	125,000
45	0.8017	6.684	11,050	19,890	132,900	10,340	18,620	124,400
46	0.7972	6.646	11,070	19,920	132,400	10,360	18,640	123,900
47	0.7927	6.609	11,080	19,940	131,900	10,370	18,660	123,300
48	0.7883	6.572	11,100	19,970	131,200	10,380	18,680	122,800
49	0.7839	6.536	11,110	20,000	130,700	10,390	18,700	122,200

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

The heat value per unit of weight generally increases as the gravity becomes lighter, but the reverse is true when quantities are measured in terms of volume.

The rather common practice of including a minimum heat value per pound in purchase specifications is not desirable. It usually defeats its purpose when the purchase is on a volume basis and in addition makes the supplier responsible for a property which he ordinarily cannot control.

**Thermal Properties of Petroleum Products** (other than heat value).<sup>1</sup> Many of the thermal properties of petroleum oils appear to vary systematically with the tem-

<sup>1</sup> Thermal Properties of Petroleum Products, NBS Misc. Pub. 97, 1933.



Table 7-17. Heats of Combustion of Volatile Petroleum Products<sup>1</sup>

Gravity		Density	Total heat of combustion at constant volume, $Q_v$			Net heat of combustion at constant pressure, $Q_p$		
Deg API at 60°F	Sp gr at 60°/60°F	Lb/gal	Cal/g	Btu/lb	Btu/gal	Cal/g	Btu/lb	Btu/gal
50	0.7796	6.500	11,120	20,020	130,100	10,400	18,720	121,700
51	0.7753	6.464	11,140	20,050	129,600	10,410	18,740	121,100
52	0.7711	6.429	11,150	20,070	129,000	10,420	18,760	120,600
53	0.7669	6.394	11,160	20,100	128,500	10,430	18,780	120,100
54	0.7628	6.360	11,180	20,120	128,000	10,440	18,800	119,500
55	0.7587	6.326	11,190	20,140	127,400	10,450	18,810	119,000
56	0.7547	6.292	11,200	20,170	126,900	10,460	18,830	118,500
57	0.7507	6.258	11,220	20,190	126,400	10,470	18,850	118,000
58	0.7467	6.225	11,230	20,210	125,800	10,480	18,870	117,500
59	0.7428	6.193	11,240	20,230	125,300	10,490	18,880	116,900
60	0.7389	6.160	11,250	20,260	124,800	10,500	18,900	116,400
61	0.7351	6.128	11,270	20,280	124,300	10,510	18,920	115,900
62	0.7313	6.097	11,280	20,300	123,700	10,520	18,930	115,400
63	0.7275	6.065	11,290	20,320	123,200	10,530	18,950	114,900
64	0.7238	6.034	11,300	20,340	122,700	10,540	18,960	114,400
65	0.7201	6.004	11,310	20,360	122,200	10,540	18,980	113,900
66	0.7165	5.973	11,320	20,380	121,700	10,550	18,990	113,400
67	0.7128	5.943	11,330	20,400	121,200	10,560	19,010	112,900
68	0.7093	5.913	11,340	20,420	120,700	10,570	19,020	112,500
69	0.7057	5.884	11,350	20,440	120,200	10,580	19,040	112,000
70	0.7022	5.855	11,360	20,460	119,800	10,580	19,050	111,500
72	0.6953	5.797	11,380	20,490	118,800	10,600	19,080	110,600
74	0.6886	5.741	11,400	20,530	117,900	10,610	19,100	109,700
76	0.6819	5.685	11,420	20,560	116,900	10,630	19,130	108,800
78	0.6754	5.631	11,440	20,600	116,000	10,640	19,150	107,900
80	0.6690	5.578	11,460	20,630	115,100	10,650	19,180	107,000
82	0.6628	5.526	11,480	20,660	114,200	10,670	19,200	106,100
84	0.6566	5.474	11,490	20,690	113,300	10,680	19,220	105,200
86	0.6506	5.424	11,510	20,720	112,400	10,690	19,240	104,400
88	0.6446	5.375	11,530	20,750	111,500	10,700	19,260	103,500
90	0.6388	5.326	11,540	20,780	110,700	10,710	19,280	102,700
92	0.6331	5.278	11,560	20,810	109,800	10,720	19,300	101,900
94	0.6275	5.232	11,570	20,830	109,000	10,740	19,320	101,100
96	0.6220	5.186	11,590	20,860	108,100	10,750	19,340	100,300
98	0.6166	5.140	11,600	20,880	107,300	10,760	19,360	99,500
100	0.6112	5.096	11,620	20,910	106,500	10,770	19,380	98,700
105	0.5983	4.988	11,650	20,970	104,600	10,790	19,420	96,800
110	0.5859	4.885	11,680	21,020	102,700	10,810	19,460	95,100
115	0.5740	4.786	11,710	21,070	100,900	10,830	19,490	93,300
120	0.5626	4.691	11,740	21,120	99,100	10,850	19,530	91,600
125	0.5517	4.599	11,760	21,170	97,400	10,860	19,560	90,000
130	0.5411	4.511	11,790	21,210	95,700	10,880	19,590	88,400
135	0.5310	4.427	11,810	21,250	94,100	10,900	19,610	86,800
140	0.5212	4.345	11,830	21,290	92,500	10,910	19,640	85,300
145	0.5118	4.267	11,850	21,330	91,000	10,920	19,660	83,900

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

Table 7-18. Heats of Combustion of Gasoline-Benzol Mixtures<sup>1</sup>

Gravity		Btu/gal, Qv. Mixtures containing 0 to 60 per cent benzol, by volume						
Deg API at 60°F	Sp gr at 60°/60°F	0	10	20	30	40	50	60
Total heat of combustion at constant volume								
40	0.8251	135,800	134,800	133,800	132,800	131,800	130,800	129,700
41	0.8203	135,200	134,200	133,200	132,200	131,200	130,100	129,000
42	0.8155	134,700	133,700	132,700	131,600	130,600	129,500	128,400
43	0.8109	134,100	133,100	132,100	131,000	130,000	128,900	127,700
44	0.8063	133,500	132,500	131,500	130,400	129,400	128,300	127,100
45	0.8017	132,900	131,900	130,900	129,900	128,800	127,700	126,400
46	0.7972	132,400	131,400	130,300	129,300	128,200	127,000	125,800
47	0.7927	131,800	130,800	129,700	128,700	127,600	126,400	125,200
48	0.7883	131,200	130,200	129,200	128,100	127,000	125,800	124,500
49	0.7839	130,700	129,600	128,600	127,500	126,400	125,200	123,800
50	0.7796	130,100	129,100	128,000	126,900	125,800	124,500	123,200
51	0.7753	129,600	128,500	127,400	126,300	125,200	123,900	122,600
52	0.7711	129,000	128,000	126,900	125,700	124,600	123,300	122,000
53	0.7669	128,500	127,400	126,300	125,200	124,000	122,700	121,300
54	0.7628	128,000	126,900	125,800	124,600	123,400	122,100	120,700
55	0.7587	127,400	126,300	125,200	124,000	122,800	121,500	120,000
56	0.7547	126,900	125,800	124,700	123,500	122,200	120,900	119,400
57	0.7507	126,400	125,200	124,100	122,900	121,700	120,300	118,800
58	0.7467	125,800	124,700	123,600	122,300	121,100	119,700	118,100
59	0.7428	125,300	124,200	123,000	122,800	120,500	119,100	117,500
60	0.7389	124,800	123,600	122,500	121,300	120,000	118,500	116,900
Net heat of combustion at constant pressure								
40	0.8251	127,300	126,700	126,000	125,300	124,700	124,000	123,200
41	0.8203	126,700	126,100	125,400	124,700	124,100	123,400	122,600
42	0.8155	126,200	125,500	124,800	124,100	123,500	122,700	122,000
43	0.8109	125,600	124,900	124,200	123,600	122,900	122,100	121,300
44	0.8063	125,000	124,300	123,700	123,000	122,300	121,500	120,700
45	0.8017	124,400	123,800	123,100	122,400	121,700	120,900	120,100
46	0.7972	123,900	123,200	122,500	121,800	121,100	120,300	119,400
47	0.7927	123,300	122,600	121,900	121,200	120,500	119,700	118,800
48	0.7883	122,800	122,100	121,400	120,700	119,900	119,100	118,200
49	0.7839	122,200	121,500	120,800	120,100	119,300	118,500	117,600
50	0.7796	121,700	121,000	120,300	119,500	118,700	117,900	117,000
51	0.7753	121,100	120,400	119,700	118,900	118,100	117,300	116,300
52	0.7711	120,600	119,900	119,200	118,400	117,600	116,700	115,700
53	0.7669	120,100	119,300	118,600	117,800	117,000	116,100	115,100
54	0.7628	119,500	118,800	118,100	117,300	116,400	115,500	114,500
55	0.7587	119,000	118,300	117,500	116,700	115,900	114,900	113,900
56	0.7547	118,500	117,700	117,000	116,200	115,300	114,400	113,300
57	0.7507	118,000	117,200	116,400	115,600	114,800	113,800	112,700
58	0.7467	117,500	116,700	115,900	115,100	114,200	113,200	112,100
59	0.7428	116,900	116,200	115,400	114,500	113,600	112,600	111,500
60	0.7389	116,400	115,600	114,800	114,000	113,100	112,100	110,900

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S). Misc. Pub. 97, 1933.

Table 7-19. Empirical Equations for Thermal Properties of Petroleum Products<sup>1</sup>

Property	Units	Empirical equation	Experimental range		Estimated accuracy, per cent
			<i>d</i>	<i>t</i>	

In engineering units: *d* = sp gr at 60°/60°F, *t* = temp, deg F; *p* = pressure, psia; unit volume of liquid = gal, measured at 60°F

Coefficient of expansion of liquid	$\frac{1}{V_{60}} \frac{dV}{dt}$	$= A + 2B(t - 60)$ [See note a]	0 51-1 00	32-200	5
Total heat of combustion at constant volume	Btu/lb	$= 22,320 - 3,780d^2$	} 0 51-0 99		1
	Btu/gal	$= 186,087d - 31,515d^2$			
Specific volume of vapor	ft <sup>3</sup> /lb	$= \frac{0.242(t + 460)}{p} \frac{(1.03 - d)}{d}$	0 51-0 80	.	10
Thermal conductivity of liquid	$\frac{\text{Btu in.}}{\text{ft}^2 \text{ hr } ^\circ\text{F}}$	$= \frac{0.813}{d} [1 - 0.0003(t - 32)]$	0 78-0 95	32-400	10
Specific heat of liquid	Btu/lb °F	$= \frac{1}{\sqrt{d}} (0.388 + 0.00045t)$	} 0 72- 096	32-750	5
	Btu/gal °F	$= \sqrt{d} (3.235 + 0.00375t)$			
Latent heat of vaporization	Btu/lb	$= \frac{1}{d} (110.9 - 0.09t)$	} 0 64-0 91	100-600	10
	Btu/gal	$= 925 - 0.75t$			
Heat content of liquid	Btu/gal	$= \sqrt{d} (3.235t + 0.001875t^2 - 105.5)$	0 72-0 96	32-750	5
Heat content of vapor	Btu/gal	$= \sqrt{d} (3.235t + 0.001875t^2 - 105.5) + 925 - 0.75t$	0 64-0 91	100-600	5

In metric units: *d* = density, g/ml at 15°C; *t* = temp, °C; *p* = pressure, atm, unit volume of liquid = ml measured at 15°C

Coefficient of expansion of liquid	$\frac{1}{V_{15}} \frac{dV}{dt}$	$= A + 2B(t - 15)$ [See note b]	0 51-1 00	0-100	5
Total heat of combustion at constant volume	Cal/g	$= 12,400 - 2,100d^2$	} 0 51-0 99		1
	Cal/ml	$= 12,400d - 2,100d^2$			
Specific volume of vapor	1/g	$= \frac{0.821(t + 273)}{p} \frac{(1.03 - d)}{d}$	0 51-0 80		10
Thermal conductivity of liquid	$\frac{\text{cal cm}}{\text{cm}^2 \text{ sec } ^\circ\text{C}}$	$= \frac{0.00028}{d} (1 - 0.00054t)$	0 78-0 95	0-200	10
Specific heat of liquid	Cal/g °C	$= \frac{1}{\sqrt{d}} (0.403 + 0.00081t)$	} 0 72-0 96	0-400	5
	Cal/ml °C	$= \sqrt{d} (0.403 + 0.00081t)$			
Latent heat of vaporization	Cal/g	$= \frac{1}{d} (60 - 0.09t)$	} 0 64-0 91	40-300	10
	Cal/ml	$= 60 - 0.09t$			
Heat content of liquid	Cal/ml	$= \sqrt{d} (0.403t + 0.000405t^2)$	0 72-0 96	0-400	5
Heat content of vapor	Cal/ml	$= 60 + (0.403 \sqrt{d} - 0.09)t + 0.000405 \sqrt{d} t^2$	0 64-0 91	40-300	5

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.), Misc. Pub. 97, 1933.<sup>a</sup>  $\log (A \times 10^6) = 0.835 + (0.70/d)$ ;  $\log (B \times 10^6) = (2.10/d) - 1.20$ .<sup>b</sup>  $\log (A \times 10^6) = 1.09 + (0.70/d)$ ;  $\log (B \times 10^6) = (2.10/d) - 0.69$ .

perature and with the density of the oils. Empirical equations have been found which represent with moderate accuracy what appear to be the most reliable experimental data at present available.

Table 7-19 contains a summary of these equations expressed in engineering units and also in metric units. Further discussion and reference tables calculated from these equations are presented in the pages following.

**Thermal Conductivity.** The data on thermal conductivity of petroleum, liquids given in Table 7-20, were calculated from the following equation:

$$K = \frac{0.813}{d} [1 - 0.0003(t - 32)]$$

where  $K$  = thermal conductivity, Btu/hr/sq ft, and per deg F per in. of thickness  
 $d$  = specific gravity of liquid at 60°/60°F  
 $t$  = temperature, deg F

The thermal conductivity of paraffin wax decreases slightly with increased temperature, about 0.1 per cent per degree Fahrenheit and probably decreases rapidly near the melting point, becoming equal to that for petroleum liquids of corresponding gravity at temperatures above the melting point.

**Example of Use of Table 7-20:** The opposite faces of a slab of petroleum asphalt, 3 in. thick, are maintained at 32 and 77°F, respectively. What is the heat per day through each square foot of the slab?

*Answer:*  $1.2 \times 24 \times 1 \times \frac{45}{3} = 432$  Btu

**Table 7-20. Thermal Conductivity of Petroleum Products<sup>1</sup>**

Temp	Liquids of various gravities						Solids	
	Deg API at 60°F						Amorphous	Crystalline
	10	20	30	40	50	60	Asphalt	Paraffin wax
	Specific gravity at 60°/60°F							
	1 0000	0 9340	0 8762	0 8251	0.7796	0 7389		
Deg F	Units: Btu/hr/sq ft, and deg F per in.							
0	0 82	0 88	0 94	1 00	1 05	1 11	1.2	1.6
200	0 77	0 83	0 88	0.94	0 99	1 05	(For temperature range, 32°F to melting point)	
400	0 72	0 77	0 83	0 88	0.93	0 98		
600	0 67	0 72	0 77	0 82				
800	0 63	0 67	0 71					
Deg C	Units: cal/sec/cm <sup>2</sup> , and deg C per cm							
0	0 00028	0 00030	0 00032	0 00034	0 00036	0 00038	0 00040	0 00056
100	0 00027	0 00028	0 00030	0 00032	0 00034	0 00036	(For temperature range, 0°C to melting point)	
200	0 00025	0.00027	0.00029	0 00030	0 00032	0.00034		
300	0 00024	0 00025	0 00027	0 00028				
400	0 00022	0.00024	0 00025					

<sup>1</sup> Thermal Properties of Petroleum Products, *NBS (U.S.) Misc. Pub. 97*, 1933.

**Specific Heat of Petroleum Oils.** The data on specific heat of petroleum oils, given in Tables 7-21 and 7-22, were calculated from the equation

$$c = \left[ \frac{1}{\sqrt{d}} (0.388 + 0.00045t) \right]$$

where  $c$  = specific heat, Btu/lb/deg F, or cal/g/deg C

$d$  = specific gravity at 60°/60°F

$t$  = temperature, deg F.

Bureau of Standards experimental results on oils from mixed-base crudes were in excellent agreement with the calculated values; whereas the results on oils from paraffin-base crudes were systematically higher by about 2 per cent; and the results on oils from naphthene-base crudes are systematically lower by about 2 per cent.

These data are considered accurate within about 5 per cent at constant pressures of 1 atm; they are probably somewhat too low for pressures much above 100 psi.

**Table 7-21. Specific Heat of Petroleum Oils of Various Gravities<sup>1</sup>**  
(In Btu per pound per degree Fahrenheit, or calories per gram per degree centigrade)

Temp, deg F	Deg API at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F							
	1.0000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	0.388	0.401	0.415	0.427	0.439	0.451	0.463	0.474
20	0.397	0.411	0.424	0.437	0.450	0.462	0.474	0.485
40	0.406	0.420	0.434	0.447	0.460	0.472	0.485	0.496
60	0.415	0.429	0.443	0.457	0.470	0.483	0.495	0.507
80	0.424	0.439	0.453	0.467	0.480	0.493	0.506	0.518
100	0.433	0.448	0.463	0.477	0.490	0.504	0.517	0.529
120	0.442	0.457	0.472	0.487	0.501	0.514	0.527	0.540
140	0.451	0.467	0.482	0.497	0.511	0.525	0.538	0.551
160	0.460	0.476	0.491	0.506	0.521	0.535	0.549	0.562
180	0.469	0.485	0.501	0.516	0.531	0.546	0.560	0.573
200	0.478	0.495	0.511	0.526	0.541	0.556	0.570	0.584
220	0.487	0.504	0.520	0.536	0.552	0.567	0.581	
240	0.496	0.513	0.530	0.546	0.562	0.577	0.592	
260	0.505	0.523	0.540	0.556	0.572	0.588	0.603	
280	0.514	0.532	0.549	0.566	0.582	0.598	0.613	
300	0.523	0.541	0.559	0.576	0.592	0.609	0.624	
320	0.532	0.550	0.568	0.586	0.603	0.619		
340	0.541	0.560	0.578	0.596	0.613	0.629		
360	0.550	0.569	0.588	0.606	0.623	0.640		
380	0.559	0.578	0.597	0.615	0.633	0.650		
400	0.568	0.588	0.607	0.625	0.643	0.661		
420	0.577	0.597	0.616	0.635	0.653			
440	0.586	0.606	0.626	0.645	0.664			
460	0.595	0.616	0.636	0.655	0.674			
480	0.604	0.625	0.645	0.665	0.684			
500	0.613	0.634	0.655	0.675	0.694			
520	0.622	0.644	0.665	0.685				
540	0.631	0.653	0.674	0.695				
560	0.640	0.662	0.684	0.705				
580	0.649	0.672	0.693	0.715				
600	0.658	0.681	0.703	0.724				
620	0.667	0.690	0.713					
640	0.676	0.699	0.722					
660	0.685	0.709	0.732					
680	0.694	0.718	0.741					
700	0.703	0.727	0.751					
720	0.712	0.737	0.761					
740	0.721	0.746	0.770					
760	0.730	0.755	0.780					
780	0.739	0.765	0.790					
800	0.748	0.774	0.799					

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

**Table 7-22. Specific Heat of Petroleum Oils of Various Gravities<sup>1</sup>**  
(In Btu per gallon per degree Fahrenheit)

Temp, deg F	Deg API at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F							
	1.0000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	3.23	3.13	3.03	2.94	2.86	2.78	2.71	2.65
20	3.31	3.20	3.10	3.01	2.92	2.85	2.77	2.71
40	3.38	3.26	3.17	3.07	2.99	2.91	2.84	2.77
60	3.46	3.33	3.24	3.14	3.06	2.97	2.90	2.83
80	3.53	3.41	3.31	3.21	3.12	3.04	2.96	2.89
100	3.61	3.49	3.38	3.28	3.19	3.10	3.02	2.95
120	3.69	3.56	3.45	3.35	3.25	3.17	3.09	3.01
140	3.76	3.63	3.52	3.41	3.32	3.23	3.15	3.08
160	3.84	3.71	3.59	3.48	3.39	3.30	3.21	3.14
180	3.91	3.78	3.66	3.55	3.45	3.36	3.28	3.20
200	3.99	3.85	3.73	3.62	3.52	3.43	3.34	3.26
220	4.06	3.92	3.80	3.69	3.58	3.49	3.40	
240	4.14	4.00	3.87	3.75	3.65	3.55	3.46	
260	4.21	4.07	3.94	3.82	3.72	3.62	3.53	
280	4.29	4.14	4.01	3.89	3.78	3.68	3.59	
300	4.36	4.21	4.08	3.96	3.86	3.75	3.65	
320	4.44	4.29	4.15	4.03	3.93	3.81		
340	4.51	4.36	4.22	4.09	3.99	3.88		
360	4.59	4.43	4.29	4.16	4.06	3.94		
380	4.66	4.50	4.36	4.23	4.12	4.01		
400	4.74	4.58	4.43	4.30	4.19	4.07		
420	4.81	4.65	4.50	4.37	4.26			
440	4.89	4.72	4.57	4.44	4.32			
460	4.96	4.79	4.64	4.50	4.39			
480	5.04	4.87	4.71	4.57	4.46			
500	5.11	4.94	4.78	4.64	4.52			
520	5.19	5.01	4.85	4.71				
540	5.26	5.08	4.92	4.78				
560	5.34	5.16	4.99	4.84				
580	5.41	5.23	5.06	4.91				
600	5.49	5.30	5.13	4.98				
620	5.56	5.37	5.20					
640	5.64	5.45	5.27					
660	5.71	5.52	5.34					
680	5.79	5.59	5.41					
700	5.86	5.66	5.49					
720	5.94	5.74	5.56					
740	6.01	5.81	5.63					
760	6.09	5.88	5.70					
780	6.16	5.95	5.77					
800	6.24	6.03	5.84					

<sup>1</sup> Thermal Properties of Petroleum Products, *NBS (U.S.) Misc. Pub. 97*, 1933.

Since the relation between true specific heat and temperature is linear, the mean specific heat between any two temperatures is equal to the true specific heat at the mean temperature.

These data do not take into account such quantities as latent heat of fusion, latent heat of vaporization, and heat of reaction (cracking).

**Specific Heat of Petroleum Asphalt.** Petroleum asphalt may be regarded thermally as a subcooled liquid with no heat of transformation from liquid to apparent solid.

Measurements of the Bureau of Standards on a sample of petroleum asphalt agreed within 2 per cent with the data given in the 10° API columns of Tables 7-21 and 7-22, which indicates that the data in these columns are probably applicable to petroleum asphalts and to the bitumen content of natural asphalts.

**Specific Heat of Asphalt Construction Mixtures.** In many practical applications, petroleum asphalt is mixed with various amounts of solids such as sand and crushed rock. The specific heat of such mixtures may be obtained from the equation

$$C_m = 0.01[(100 - x)C_a + xC_s]$$

where  $x$  = per cent, by weight, of solids

$C$  = specific heat

$a$ ,  $s$ , and  $m$  = asphalt, solids, and mixture

The relation  $C_s = 0.18 + 0.00006t^\circ\text{F}$  may be used for the solid constituents.

**Latent Heat of Vaporization.** The data on latent heat of vaporization of petroleum oils, given in Table 7-23, were calculated from the equation

$$L = \frac{1}{d} (110.9 - 0.09t)$$

where  $L$  = latent heat of vaporization, Btu/lb

$d$  = specific gravity of liquid at 60°/60°F

$t$  = temperature, deg F

This equation yields the following convenient relation:

$$L (\text{Btu/lb}) \times \text{density (lb/gal)} = 8.33722Ld = 925 - 0.75t (\text{Btu/gal})$$

which indicates that the latent heat of vaporization per unit of volume of liquid (60°F) is dependent only on the temperature of vaporization. Thus the values given in the second column of Table 7-23 are applicable to any petroleum oil, regardless of gravity. The values given in the other columns are applicable, in general, to all cases of vaporization of petroleum products in which the temperature of vaporization and the gravity of the condensate are known.

The estimated accuracy of the data in Table 7-23 is 10 per cent, when vaporization occurs at sensibly constant temperature and at pressures below 50 psi, without chemical change. They are probably too low by more than this amount for petroleum products containing large quantities of the lower members of the aromatic series and too high for vaporization at high pressures.

**Total Heat Content of Petroleum Liquids.** Calculations of the quantities of heat involved in the heating and cooling of fluids are very simple when use is made of the thermodynamic function called heat content (also called total heat and enthalpy). For this reason, data on specific and latent heats have been combined to yield the heat-content data given in Tables 7-24 and 7-25. Strictly speaking, the data in these tables represent heat content at 1 atm pressure, since they are based on measurements made at atmospheric pressures. The magnitude of the change of heat content with pressure (temperature constant) is small, however, being comparable with the estimated accuracy of these data in general for pressures below 1,000 psi.

Following usual practice, the heat content of liquid has been arbitrarily assigned

Table 7-23. Latent Heat of Vaporization of Petroleum Oils of Various Gravities<sup>1</sup>  
 (In Btu per pound)

Temp, deg F	Latent heat, 10°-80° API oils, Btu/gal	Deg API at 60°F						
		20	30	40	50	60	70	80
		Specific gravity at 60°/60°F						
		0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	925	..	..	...	142	150	158	166
20	910	.	.	.	140	148	155	163
40	895	.	.	.	138	145	153	160
60	880	.	.	.	135	143	150	158
80	865	.	.	...	133	140	148	155
100	850	.	.	123	131	138	145	152
120	835	.	.	121	128	135	143	150
140	820	.	.	119	126	133	140	147
160	805	.	.	117	124	131	137	144
180	790	.	.	115	121	128	135	142
200	775	.	106	113	119	126	132	139
220	760	.	104	110	117	123	130	
240	745	.	102	108	115	121	127	
260	730	.	100	106	112	118	125	
280	715	..	98	104	110	116	122	
300	700	90	96	102	108	113	119	
320	685	88	94	99	105	111		
340	670	86	92	97	103	109		
360	655	84	90	95	101	106		
380	640	82	88	93	98	104		
400	625	80	85	91	96	101		
420	610	78	83	89	94			
440	595	76	81	86	91			
460	580	74	79	84	89			
480	565	73	77	82	87			
500	550	71	75	80	85			
520	535	69	73	78				
540	520	67	71	75				
560	505	65	69	73				
580	490	63	67	71				
600	475	61	65	69				
620	460	59	63					
640	445	57	61					
660	430	55	59					
680	415	53	57					
700	400	51	55					
720	385	49	53					
740	370	47	51					
760	355	45	48					
780	340	44	46					
800	325	42	44					

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.



the value zero at 32°F. Thus, for all practical purposes, the heat content of petroleum liquids  $H_1$  is given by the equation

$$H_1 = \int_{32}^t c \, dt$$

where  $H_1$  = total heat content above 32°F

$c$  = specific heat

$d$  = specific gravity

$t$  = temp, deg F

The estimated accuracy of the data in Table 7-24 as heat content at 1 atm pressure is 5 per cent. The data are probably too low by more than this amount in the neighborhood of the critical point.

The estimated accuracy of the data in Table 7-25 is as follows: 5 per cent for vapor saturated at atmospheric pressure or below; 10 per cent for vapor saturated at any temperature and pressure; 15 per cent for vapor at any pressure and superheated by any amount. The data do not take into account heats of chemical reactions. As the specific heat data are too low and the data on latent heat of vaporization too high for the higher pressures, there is considerable compensation in the resultant values for heat content. There is an analogous compensation in the case of vapors rich in aromatics.

**Example of Use of Table 7-24:** How much heat is required to raise the temperature of a 30°API oil from 70 to 500°F? The result is obtained from the table as follows:

$$\begin{array}{rcl} \text{Heat content at 500°F} & = & 1,854 \text{ Btu/gal} \\ \text{Heat content at 70°F} & = & 122 \text{ Btu/gal} \\ \text{Heat required (difference)} & = & 1,732 \text{ Btu/gal} \end{array}$$

**Example of Use of Table 7-25:** How much heat must be removed in a condenser in order to change vapor at 500°F into liquid at 80°F, the gravity of the condensate being 50°API at 60°F? The result is obtained from the tables as follows:

$$\begin{array}{rcl} \text{Heat content of vapor at 500°F} & = & 2,299 \text{ Btu/gal (Table 7-25)} \\ \text{Heat content of liquid at 80°F} & = & 146 \text{ Btu/gal (Table 7-24)} \\ \text{Heat removed (difference)} & = & 2,153 \text{ Btu/gal} \end{array}$$

**Heat Content of Asphalt.** The data given in Table 7-26, on the heat content of asphalts containing various percentages of mineral matter, were calculated from the following equation:

$$H_a = (0.388t + 0.000225t^2 - 12.65)(1 - 0.01x) + (0.18t + 0.00003t^2 - 5.76)0.01x$$

where  $t$  = temperature, deg F

$x$  = per cent, by weight, of mineral matter

The data contained in the column marked "0 per cent" are applicable to the bitumen content of natural asphalts and to petroleum asphalts which usually contain only small amounts of mineral matter. The data given in the columns marked "10 per cent" to "80 per cent," inclusive, are applicable to natural asphalts and to mixtures of natural or petroleum asphalts with known amounts of mineral matter. In using these data, it should be noted that the content of mineral matter, as used here, includes the so-called "free-carbon" content of the asphalt.

The values of heat content given in Table 7-26 are too small for products containing water or wax by amounts which vary in proportion to the quantities of these materials present.

**Example of Use of Table 7-26:** How much heat is required to raise the temperature of asphalt containing 10 per cent of mineral matter from 60 to 400°F?

Heat content at 400°F, 168 Btu, minus heat content at 60°F, 11 Btu, equals 157 Btu per lb.

**Table 7-24. Heat Content of Petroleum Liquids of Various Gravities<sup>1</sup>**  
(In Btu per gallon. Unit is 1 gal at 60°F)

Temp, deg F	Deg API at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60° F							
	1.0000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	-105	-102	-99	-96	-93	-91	-88	-86
10	-73	-70	-68	-66	-64	-64	-61	-60
20	-40	-39	-37	-36	-35	-34	-34	-33
32	0	0	0	0	0	0	0	0
40	+27	+26	+25	+24	+24	+23	+23	+22
50	61	59	57	55	54	52	51	50
60	95	92	89	86	84	82	80	78
70	130	126	122	118	115	112	109	106
80	165	160	155	150	146	142	138	135
90	201	194	188	182	177	173	168	164
100	237	229	222	215	209	204	198	194
110	273	264	256	248	241	235	229	223
120	310	300	290	281	273	267	260	253
130	347	335	325	315	306	299	291	284
140	384	371	360	349	339	331	322	314
150	422	408	395	383	372	363	354	345
160	460	445	431	418	406	396	386	376
170	499	482	467	453	440	429	418	408
180	538	520	503	488	475	462	451	440
190	577	558	540	524	509	496	484	472
200	617	596	577	560	544	530	517	504
210	657	635	615	596	580	564	550	537
220	697	674	652	633	615	599	584	570
230	738	713	691	670	651	634	618	603
240	779	753	729	707	688	669	653	637
250	820	793	768	745	724	705	688	671
260	862	833	807	783	761	741	723	705
270	904	874	847	822	799	778	758	740
280	947	915	887	861	836	814	794	775
290	990	957	927	900	874	851	830	810
300	1,034	999	968	939	913	889	866	846
310	1,078	1,041	1,009	979	952	926	903	881
320	1,122	1,084	1,050	1,019	911	964	940	917
330	1,166	1,127	1,092	1,059	1,030	1,002	977	954
340	1,211	1,170	1,134	1,100	1,070	1,041	1,015	981
350	1,256	1,214	1,176	1,141	1,110	1,080	1,053	1,028
360	1,302	1,258	1,219	1,183	1,150	1,119	1,091	1,065
370	1,348	1,303	1,262	1,225	1,190	1,159	1,130	1,103
380	1,395	1,348	1,306	1,267	1,231	1,199	1,169	1,141
390	1,441	1,393	1,349	1,309	1,273	1,239	1,208	1,179

Table 7-24. Heat Content of Petroleum Liquids of Various Gravities.<sup>1</sup> (Continued)

Temp, deg F	Deg API at 60°F							
	10	15	20	25	30	35	40	45
	Specific gravity at 60°/60°F							
	1.0000	0.9659	0.9340	0.9042	0.8762	0.8498	0.8251	0.8017
400	1,489	1,463	1,439	1,416	1,393	1,372	1,352	1,333
410	1,536	1,510	1,485	1,461	1,438	1,416	1,395	1,375
420	1,584	1,557	1,531	1,506	1,483	1,460	1,439	1,418
430	1,632	1,604	1,578	1,552	1,528	1,505	1,483	1,461
440	1,681	1,652	1,625	1,598	1,573	1,549	1,527	1,505
450	1,730	1,700	1,672	1,645	1,619	1,595	1,571	1,549
460	1,779	1,749	1,720	1,692	1,666	1,640	1,616	1,593
470	1,829	1,798	1,768	1,740	1,712	1,686	1,661	1,638
480	1,879	1,847	1,816	1,787	1,759	1,732	1,707	1,683
490	1,930	1,897	1,865	1,835	1,806	1,779	1,753	1,728
500	1,981	1,947	1,914	1,884	1,854	1,826	1,799	1,774
510	2,032	1,997	1,964	1,932	1,902	1,873	1,846	1,820
520	2,084	2,048	2,014	1,981	1,950	1,921	1,893	1,866
530	2,136	2,099	2,064	2,031	1,999	1,969	1,940	1,912
540	2,188	2,151	2,115	2,081	2,048	2,017	1,988	1,959
550	2,241	2,203	2,166	2,131	2,097	2,066	2,036	2,007
560	2,294	2,255	2,217	2,182	2,147	2,115	2,084	2,054
570	2,348	2,308	2,269	2,233	2,197	2,164	2,133	2,102
580	2,402	2,361	2,321	2,284	2,248	2,214	2,182	2,150
590	2,456	2,414	2,373	2,335	2,299	2,264	2,231	2,199
600	2,511	2,467	2,426	2,387	2,350	2,314	2,281	2,248
610	2,566	2,521	2,479	2,440	2,402	2,365	2,331	2,297
620	2,621	2,576	2,533	2,492	2,454	2,416	2,381	2,347
630	2,677	2,631	2,587	2,545	2,506	2,467	2,432	2,397
640	2,733	2,686	2,641	2,599	2,558	2,519	2,483	2,447
650	2,789	2,741	2,696	2,652	2,611	2,571	2,534	2,497
660	2,846	2,797	2,751	2,706	2,665	2,624	2,586	2,548
670	2,903	2,854	2,806	2,761	2,718	2,677	2,638	2,600
680	2,961	2,911	2,862	2,815	2,772	2,730	2,690	2,651
690	3,019	2,968	2,918	2,871	2,826	2,783	2,743	2,703
700	3,078	3,025	2,974	2,927	2,881	2,837	2,796	2,756
710	3,137	3,083	3,031	2,983	2,936	2,891	2,849	2,809
720	3,196	3,141	3,088	3,039	2,991	2,946	2,903	2,862
730	3,255	3,199	3,146	3,095	3,047	3,001	2,957	2,915
740	3,315	3,258	3,204	3,152	3,103	3,056	3,011	2,969
750	3,376	3,318	3,262	3,210	3,159	3,111	3,066	3,023
760	3,436	3,377	3,321	3,268	3,216	3,167	3,121	3,078
770	3,497	3,437	3,380	3,326	3,273	3,224	3,177	3,131
780	3,559	3,498	3,440	3,384	3,331	3,280	3,232	3,186
790	3,621	3,558	3,499	3,443	3,389	3,337	3,289	3,242
800	3,683	3,619	3,559	3,502	3,447	3,395	3,345	3,297

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

**Table 7-25. Heat Content of Petroleum Vapors<sup>1</sup>**  
 (In Btu per gallon of condensed vapor)

Temp, deg F	Deg API at 60°F						
	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F						
	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0		.	.	.....	834	837	839
10		.	.	.....	855	856	858
20		.	.	.....	876	876	877
32		.	.	.....	901	901	901
40		.	.	.....	918	918	917
50		...	....	941	940	939	937
60		.	....	964	962	960	958
70		.	....	987	984	981	979
80		.	....	1,011	1,007	1,003	1,000
90		.	....	1,035	1,030	1,025	1,022
100		.	1,065	1,059	1,054	1,048	1,044
110		.	1,090	1,083	1,078	1,071	1,066
120		.	1,116	1,108	1,102	1,095	1,088
130		.	1,142	1,133	1,126	1,118	1,111
140		....	1,169	1,159	1,151	1,142	1,134
150	...	1,208	1,196	1,185	1,176	1,166	1,157
160	...	1,236	1,223	1,211	1,201	1,191	1,181
170	....	1,264	1,250	1,238	1,226	1,216	1,205
180	....	1,293	1,278	1,265	1,252	1,241	1,230
190	....	1,322	1,306	1,292	1,278	1,266	1,254
200	1,371	1,352	1,335	1,319	1,305	1,292	1,279
210	1,402	1,382	1,364	1,347	1,332	1,318	1,304
220	1,434	1,412	1,393	1,375	1,359	1,344	1,330
230	1,466	1,443	1,422	1,404	1,386	1,371	1,356
240	1,498	1,474	1,452	1,433	1,414	1,398	1,382
250	1,530	1,505	1,482	1,462	1,442	1,425	1,409
260	1,563	1,537	1,513	1,491	1,471	1,453	1,435
270	1,597	1,569	1,544	1,521	1,500	1,481	1,462
280	1,630	1,602	1,576	1,551	1,529	1,509	1,490
290	1,664	1,635	1,607	1,582	1,559	1,537	1,518
300	1,699	1,668	1,639	1,613	1,589	1,566	1,546
310	1,734	1,701	1,671	1,644	1,619	1,595	1,574
320	1,769	1,735	1,704	1,676	1,649	1,625	1,602
330	1,804	1,769	1,737	1,708	1,680	1,655	1,631
340	1,840	1,804	1,770	1,740	1,711	1,685	1,651
350	1,876	1,839	1,804	1,772	1,742	1,715	1,690
360	1,913	1,874	1,838	1,805	1,774	1,746	1,720
370	1,950	1,910	1,872	1,838	1,806	1,777	1,750
380	1,988	1,946	1,907	1,871	1,839	1,809	1,781
390	2,026	1,982	1,942	1,905	1,872	1,840	1,811

Table 7-25. Heat Content of Petroleum Vapors.<sup>1</sup> (Continued)

Temp, deg F	Deg API at 60°F							
	15	20	25	30	35	40	45	50
	Specific gravity at 60°/60°F							
	0.9659	0.9340	0.9042	0.8762	0.8498	0.8251	0.8017	0.7796
400	2,088	2,064	2,041	2,018	1,997	1,977	1,958	1,939
410	2,127	2,102	2,078	2,055	2,033	2,013	1,993	1,974
420	2,167	2,141	2,116	2,093	2,070	2,049	2,028	2,009
430	2,207	2,180	2,154	2,130	2,107	2,085	2,064	2,044
440	2,247	2,220	2,193	2,168	2,144	2,122	2,100	2,079
450	2,288	2,260	2,232	2,207	2,182	2,159	2,136	2,115
460	2,329	2,300	2,272	2,246	2,220	2,196	2,173	2,151
470	2,370	2,340	2,312	2,285	2,258	2,234	2,210	2,187
480	2,412	2,381	2,352	2,324	2,297	2,272	2,248	2,224
490	2,454	2,423	2,393	2,364	2,336	2,310	2,286	2,262
500	2,497	2,464	2,434	2,404	2,376	2,349	2,324	2,299
510	2,540	2,506	2,475	2,445	2,416	2,388	2,362	2,337
520	2,583	2,549	2,516	2,485	2,456	2,428	2,401	2,375
530	2,627	2,592	2,558	2,526	2,496	2,468	2,440	2,413
540	2,671	2,635	2,601	2,568	2,537	2,508	2,479	2,452
550	2,715	2,678	2,644	2,610	2,578	2,549	2,519	2,491
560	2,760	2,722	2,687	2,652	2,620	2,589	2,559	2,530
570	2,805	2,766	2,730	2,695	2,662	2,630	2,600	2,570
580	2,851	2,811	2,774	2,738	2,704	2,672	2,640	2,610
590	2,896	2,856	2,818	2,781	2,746	2,714	2,681	2,651
600	2,942	2,901	2,862	2,825	2,789	2,756	2,723	2,692
610	2,989	2,947	2,907	2,869	2,832	2,798	2,765	2,733
620	3,036	2,993	2,952	2,914	2,876	2,841	2,807	2,774
630	3,083	3,039	2,998	2,958	2,920	2,884	2,850	2,816
640	3,131	3,086	3,044	3,003	2,964	2,928	2,892	2,858
650	3,179	3,133	3,090	3,049	3,009	2,972	2,935	2,900
660	3,227	3,181	3,136	3,095	3,054	3,016	2,978	2,943
670	3,276	3,229	3,183	3,141	3,100	3,061	3,022	2,986
680	3,326	3,277	3,230	3,187	3,145	3,105	3,066	3,030
690	3,375	3,325	3,278	3,234	3,191	3,150	3,111	3,074
700	3,425	3,374	3,327	3,281	3,237	3,196	3,156	3,118
710	3,475	3,424	3,375	3,328	3,284	3,242	3,201	3,162
720	3,526	3,473	3,424	3,376	3,331	3,288	3,247	3,207
730	3,577	3,523	3,473	3,424	3,378	3,334	3,292	3,252
740	3,628	3,574	3,522	3,473	3,426	3,381	3,339	3,297
750	3,680	3,625	3,572	3,522	3,474	3,428	3,385	3,343
760	3,732	3,676	3,623	3,571	3,522	3,476	3,432	3,389
770	3,785	3,727	3,673	3,621	3,571	3,524	3,479	3,435
780	3,838	3,780	3,724	3,671	3,620	3,572	3,526	3,482
790	3,891	3,832	3,775	3,721	3,670	3,621	3,574	3,529
800	3,944	3,884	3,827	3,772	3,720	3,670	3,622	3,576

NOTE: The unit of mass used here, because of its practical usefulness, is the weight of petroleum vapor which, when condensed, is equal to the weight of 1 gal of liquid at 60°F.

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

**Table 7-26. Heat Content of Asphalt<sup>1</sup>**  
(In Btu per pound)

Temp, deg F	Heat content of asphalts containing 0 to 80 per cent mineral matter, by weight <sup>1</sup>							
	0	10	20	30	40	50	60	80
0	-13	-12	-11	-11	-10	-9	-8	-7
10	-9	-8	-8	-7	-7	-6	-6	-5
20	-5	-5	-4	-4	-4	-3	-3	-3
32	0	0	0	0	0	0	0	0
40	+3	+3	+3	+3	+2	+2	+2	+2
50	7	7	6	6	6	5	5	4
60	11	11	10	10	9	8	8	6
70	16	15	14	13	12	11	10	9
80	20	19	18	17	15	14	13	11
90	24	23	21	20	19	17	16	13
100	28	27	25	24	22	21	19	16
110	33	31	29	27	25	24	22	18
120	37	35	33	31	29	27	25	20
130	42	39	37	35	32	30	28	23
140	46	43	41	38	36	33	30	25
150	51	48	45	42	39	36	33	28
160	55	52	49	46	43	40	36	30
170	60	57	53	50	46	43	39	33
180	65	61	57	53	50	46	42	35
190	69	65	61	57	53	49	45	37
200	74	70	66	61	57	53	48	40
210	79	74	70	65	61	56	52	42
220	84	79	74	69	64	60	55	45
230	89	83	78	73	68	63	58	47
240	93	88	83	77	72	66	61	50
250	98	93	87	81	75	70	64	52
260	103	97	91	85	79	73	67	55
270	108	102	96	89	83	77	70	58
280	114	107	100	94	87	80	74	60
290	119	112	105	98	91	84	77	63
300	124	117	109	102	95	87	80	65
310	129	122	114	106	99	91	83	68
320	135	127	119	111	103	95	87	71
330	140	132	123	115	107	98	90	73
340	145	137	128	120	111	102	94	76
350	151	142	133	124	115	106	97	79
360	156	147	138	128	119	110	100	82
370	162	152	142	133	123	113	104	84
380	167	157	147	137	127	117	107	87
390	173	163	152	142	131	121	111	90
400	179	168	157	146	136	125	114	93
420	190	178	167	155	144	133	121	98
440	202	189	177	165	153	140	128	104
460	213	200	187	174	161	148	135	109
480	225	212	198	184	170	156	143	115
500	238	223	208	194	179	165	150	121

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

Table 7-27. Thermal Expansion of Volatile Petroleum Liquids<sup>1</sup>

Normal bubble point, deg F	Vapor pressure, psig				Approx gravity, at 60°F		Expansion coefficients		Lb fluid per lb water capacity, hydrostatic pressure, at	
	70°F	90°F	100°F	130°F	Specific	Deg API	A × 10 <sup>6</sup>	B × 10 <sup>7</sup>	100°F	130°F
-50	126	171	197	291	0 501	151 5	170	98	0 461	0 428
-48	121	165	190	281	0 504	149 5	167	93	0 465	0 433
-46	116	159	183	272	0 507	147 5	164	88	0 469	0 438
-44	111	153	176	263	0 510	146 0	161	83	0 473	0 442
-42	107	147	170	254	0 513	144 5	158	78	0 477	0 447
-40	103	141	164	246	0 516	142 5	155	74	0 481	0 451
-38	99	136	158	238	0 519	141 0	152	70	0 485	0 455
-36	95	131	152	230	0 522	139 5	150	67	0 488	0 459
-34	91	126	147	222	0 525	138 0	147	63	0 492	0 463
-32	87	121	141	214	0 528	136 5	145	60	0 495	0 467
-30	83	117	136	207	0 531	135 0	142	57	0 498	0 471
-28	80	112	131	200	0 533	134 0	140	55	0 501	0 474
-26	76	108	126	193	0 536	132 5	138	53	0 504	0 478
-24	73	104	121	187	0 538	131 5	137	51	0 506	0 481
-22	70	100	117	180	0 540	130 5	135	49	0 509	0 484
-20	67	96	112	174	0 542	129 5	134	47	0 511	0 487
-18	64	92	108	168	0 544	128 5	132	46	0 513	0 489
-16	61	88	104	162	0 546	127 5	131	44	0 516	0 492
-14	58	84	100	157	0 548	125 6	129	43	0 518	0 494
-12	56	81	96	151	0 550	125 5	128	42	0 520	0 496
-10	53	78	92	146	0 552	125 0	127	41	0 522	0 498
-8	51	75	89	141	0 553	124 0	126	40	0 523	0 500
-6	48	71	85	136	0 555	123 5	125	39	0 525	0 502
-4	46	68	82	131	0 556	123 0	124	38	0 526	0 503
-2	44	66	78	126	0 557	122 5	124	37	0 528	0 505
0	42	63	75	122	0 558	122 0	123	37	0 529	0 506
2	40	60	72	117	0 560	121 0	122	36	0 531	0 508
4	38	57	69	113	0 561	120 5	121	35	0 532	0 509
6	36	55	66	109	0 562	120 0	120	34	0 533	0 511
8	34	52	64	105	0 564	119 5	119	33	0 535	0 512
10	32	50	61	101	0 565	119 0	119	33	0 536	0 514
12	30	48	58	97	0 567	118 0	118	32	0 538	0 516
14	29	46	56	94	0 568	117 5	117	31	0 540	0 518
16	27	43	53	90	0 570	117 0	116	31	0 542	0 520
18	26	41	51	87	0 572	116 0	115	30	0 544	0 522
20	24	39	49	84	0 574	115 0	113	29	0 547	0 525
22	23	37	46	80	0 576	114 0	112	28	0 549	0 527
24	21	36	44	77	0 578	113 0	111	27	0 551	0 530
26	20	34	42	74	0 580	112 5	110	26	0 553	0 532
28	19	32	40	72	0 582	111 5	109	26	0 555	0 535
30	17	30	38	69	0 584	111 0	108	25	0 558	0 537
32	16	29	37	66	0 586	110 0	107	24	0 560	0 540
34	15	27	35	63	0 588	109 0	106	24	0 562	0 542
36	14	26	33	61	0 590	108 0	105	23	0 564	0 544
38	13	24	31	58	0 592	107 0	104	22	0 567	0 547
40	12	23	30	56	0 595	106 0	102	21	0 570	0 550
45	9	20	26	50	0 600	104 5	100	20	0 575	0 556
50	7	17	22	45	0 605	102 5	98	19	0 580	0 561
55	5	14	19	40	0 610	100 5	96	17	0 585	0 567
60	3	11	16	35	0 615	98 5	94	16	0 590	0 573
70	0	7	11	28	0 620	96 5	92	15	0 596	0 579

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

Table 7-28. Thermal Expansion of Petroleum Asphalts and Fluxes<sup>1</sup>

Temp, °F	$\frac{V_{60}}{V_t}$	Temp, °F	$\frac{V_{60}}{V_t}$	Temp, °F	$\frac{V_{60}}{V_t}$	Temp, °F	$\frac{V_{60}}{V_t}$	Temp, °F	$\frac{V_{60}}{V_t}$
0	1.0205	100	0.9864	200	0.9527	300	0.9195	400	0.8869
2	1.0198	102	0.9857	202	0.9520	302	0.9188	402	0.8863
4	1.0191	104	0.9850	204	0.9513	304	0.9181	404	0.8856
6	1.0185	106	0.9844	206	0.9506	306	0.9175	406	0.8850
8	1.0178	108	0.9837	208	0.9500	308	0.9168	408	0.8843
10	1.0171	110	0.9830	210	0.9493	310	0.9162	410	0.8837
12	1.0164	112	0.9823	212	0.9486	312	0.9155	412	0.8831
14	1.0157	114	0.9816	214	0.9480	314	0.9149	414	0.8824
16	1.0150	116	0.9810	216	0.9473	316	0.9142	416	0.8818
18	1.0143	118	0.9803	218	0.9466	318	0.9135	418	0.8811
20	1.0137	120	0.9796	220	0.9460	320	0.9129	420	0.8805
22	1.0130	122	0.9789	222	0.9453	322	0.9122	422	0.8799
24	1.0123	124	0.9783	224	0.9446	324	0.9116	424	0.8792
26	1.0116	126	0.9776	226	0.9440	326	0.9109	426	0.8786
28	1.0109	128	0.9769	228	0.9433	328	0.9103	428	0.8779
30	1.0102	130	0.9762	230	0.9426	330	0.9096	430	0.8773
32	1.0095	132	0.9755	232	0.9420	332	0.9090	432	0.8767
34	1.0089	134	0.9749	234	0.9413	334	0.9083	434	0.8760
36	1.0082	136	0.9742	236	0.9406	336	0.9077	436	0.8754
38	1.0075	138	0.9735	238	0.9400	338	0.9070	438	0.8747
40	1.0068	140	0.9728	240	0.9393	340	0.9064	440	0.8741
42	1.0061	142	0.9722	242	0.9386	342	0.9057	442	0.8735
44	1.0054	144	0.9715	244	0.9380	344	0.9051	444	0.8728
46	1.0048	146	0.9708	246	0.9373	346	0.9044	446	0.8722
48	1.0041	148	0.9701	248	0.9367	348	0.9038	448	0.8716
50	1.0034	150	0.9695	250	0.9360	350	0.9031	450	0.8709
52	1.0027	152	0.9688	252	0.9353	352	0.9025	452	0.8703
54	1.0020	154	0.9681	254	0.9347	354	0.9018	454	0.8697
56	1.0014	156	0.9674	256	0.9340	356	0.9012	456	0.8690
58	1.0007	158	0.9668	258	0.9333	358	0.9005	458	0.8684
60	1.0000	160	0.9661	260	0.9327	360	0.8999	460	0.8678
62	0.9993	162	0.9654	262	0.9320	362	0.8992	462	0.8671
64	0.9986	164	0.9647	264	0.9313	364	0.8986	464	0.8665
66	0.9980	166	0.9641	266	0.9307	366	0.8979	466	0.8659
68	0.9973	168	0.9634	268	0.9300	368	0.8973	468	0.8652
70	0.9966	170	0.9627	270	0.9294	370	0.8966	470	0.8646
72	0.9959	172	0.9620	272	0.9287	372	0.8960	472	0.8640
74	0.9952	174	0.9614	274	0.9280	374	0.8953	474	0.8633
76	0.9945	176	0.9607	276	0.9274	376	0.8947	476	0.8627
78	0.9939	178	0.9600	278	0.9267	378	0.8940	478	0.8621
80	0.9932	180	0.9594	280	0.9260	380	0.8934	480	0.8614
82	0.9925	182	0.9587	282	0.9254	382	0.8927	482	0.8608
84	0.9918	184	0.9580	284	0.9247	384	0.8921	484	0.8602
86	0.9912	186	0.9573	286	0.9241	386	0.8914	486	0.8595
88	0.9905	188	0.9567	288	0.9234	388	0.8908	488	0.8589
90	0.8998	190	0.9560	290	0.9228	390	0.8901	490	0.8583
92	0.8991	192	0.9553	292	0.9221	392	0.8895	492	0.8577
94	0.8984	194	0.9547	294	0.9214	394	0.8888	494	0.8570
96	0.8978	196	0.9540	296	0.9208	396	0.8882	496	0.8564
98	0.8971	198	0.9533	298	0.9201	398	0.8876	498	0.8558
100	0.8964	200	0.9527	300	0.9195	400	0.8869	500	0.8552

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933



**Thermal Expansion of Petroleum Products.** The thermal expansion of a particular product, *e.g.*, liquefied petroleum gas, may be estimated from Table 7-27 if any one of the following characteristics is known: normal bubble point,<sup>1</sup> vapor pressure,<sup>1</sup> or density.

The expansion coefficients *A* and *B* given in Table 7-27 are defined by the equation

$$V_t = V_{60} [1 + A(t - 60) + B(t - 60)^2]$$

The values given in the last two columns of Table 7-27 represent the maximum charge for each 1 lb water capacity of container at 60°F, which will not completely fill the container with liquid at 100 or 130°F. The estimated accuracy is 5 per cent.

The data were compiled from experimental work on propane, *n*-butane, isobutane, *n*-pentane, and isopentane, using mixture rules. Expansion data given in "International Critical Tables," Vol. III, indicate that these hydrocarbons of the paraffin series expand less rapidly than hydrocarbons of other series with corresponding densities and, conversely, that these paraffin series hydrocarbons expand more rapidly than those of other series with corresponding vapor pressures at a given temperature. Therefore, in cases involving safety, it is desirable that values in the last two columns be chosen from a determination of vapor pressure rather than density, since some commercial products are known to contain variable amounts of hydrocarbons other than the paraffin series.

**Example 1:** What is the maximum weight of material having a vapor pressure of 100 psig at 70°F, which can be charged into a cylinder of 90 lb water capacity at 60°F which will not completely fill the cylinder with liquid at 130°F?

**Answer:**  $0.454 \times 90 = 40.86$  lb.

**Example 2:** What is the maximum weight of material having a normal bubble point of 20°F, which can be charged into an insulated tank car of 8,000 lb water capacity at 60°F in order to be free from hydrostatic pressure at 100°F?

**Answer:**  $0.547 \times 8,000 = 4,376$  lb.

Although it is generally believed that California oils have a considerably higher rate of expansion than do oils from the Central and Eastern states, the Bureau of Standards notes that this has not been found to be the case and that the slightly higher rate is not sufficient to cause an appreciable error in the results given in Tables 7-27 and 7-28.

**Table 7-29. Coefficients of Expansion, Petroleum Asphalt**

Temp Range, Deg F	Mean Coefficient of Expansion
60-150	0.00035
60-250	0.00036
60-350	0.00037
60-450	0.00038

**Thermal Expansion of Petroleum Asphalts and Fluxes.** Values of  $V_{60}/V_t$  given in Table 7-28 represent volumes at 60°F occupied by a unit volume at indicated temperatures, *t*°F. For example, 1 gal of petroleum asphalt measured at 350°F will have a volume of 0.9031 gal at 60°F. This table is similar to Table 7-14 and, in fact, may be considered as a

supplementary correction table for the gravity range 0 to 15°F.

Corresponding calculated coefficients of expansion are as shown in Table 7-29. Products containing wax, gas bubbles, or nonbituminous materials have expansions which differ from those of the table in proportion to the amount present.

**Example:** If the volume of a given quantity of petroleum asphalt is 10,000 gal at 350°F, what is its volume at 60°F?

**Answer:**  $V_{60} = 10,000 \times 0.9031 = 9,031$  gal.

**Specific Volume of Petroleum Vapor.** The data given in Table 7-30 on specific volume *V* were calculated by means of the equation  $pVM = RT$  using  $p = 1$  standard

<sup>1</sup> The vapor pressure of a many-component liquid, as used here, is defined as the equilibrium pressure on a two-phase system composed of a relatively large amount of liquid and such a small volume of vapor that any decrease in the vapor volume would not alter the pressure appreciably. The temperature at which the vapor pressure, as defined above, is equal to one standard atmosphere is designated the normal bubble point.

atmosphere,  $R = 0.7303$ ,  $T = \text{deg F} + 460$ , and values of molecular weight  $M$  obtained from the equation

$$\frac{1}{M} = 0.0001644 (\text{deg API}) - 0.000972$$

which is equivalent to

$$M = 1.03(v - 43) = \frac{44.29d}{1.03 - d}$$

where  $v$  = molecular volume of liquid at 60°F

$d$  = specific gravity of liquid at 60°/60°F

The above relations between molecular weight and liquid density are fair approximations for the lighter hydrocarbons, propane, butane, and pentane, and represent an average of the experimental results on petroleum distillates (20 to 80° API).

The data given in Table 7-30 apply to petroleum distillates in general, with the following estimated accuracies for various ranges of liquid gravity: 20 to 35° API, 50 per cent; 35 to 50° API, 25 per cent; 50 to 100° API, 10 per cent; and 100 to 150° API, 5 per cent. The tabulated values are probably too high for paraffin-base distillates and too low for naphthene-base distillates and those rich in aromatics.

Saturation temperatures frequently differ considerably for different petroleum products of the same gravity. Saturation temperatures or normal dew points are indicated roughly in Table 7-30 by means of the staggered lines. Many of the values above the staggered lines are hypothetical values which are useful for rapid estimations of specific volumes at reduced pressures.

The specific volume  $V$  at any desired temperature and pressure may be obtained conveniently from

$$V = \frac{V_1}{p \text{ (atm)}} = \frac{760V_1}{p \text{ (mm Hg)}} = \frac{14.7V_1}{p \text{ (psia)}} = \frac{30V_1}{p \text{ (in. Hg)}}$$

selecting  $V_1$  from Table 7-30 corresponding to the desired temperature and liquid gravity.

**Example:** Crude oil having the following fractional distillation characteristics: 5 per cent over at 179°F, gravity 75.0° API; 10 per cent, 229°F, 68.9° API; 15 per cent, 270°F, 63.1° API; 20 per cent, 297°F, 58.4° API; 25 per cent, 327°F, 55.4° API; 30 per cent, 352°F, 52.7° API; 35 per cent, 394°F, 49.9° API, is heated in a fire still at such a rate as to yield 500 gal of distillate per hr. If the vapor outlet from the still is 12 in. in diameter, what is the velocity of the vapors? Table 7-30 indicates that the specific volume of the vapors of each fraction is approximately 30 cu ft per gal of distillate. Thus,

$$500 \times 30 = 15,000 \text{ cu ft per hr}$$

flow through an area of  $\pi/4 = 0.785$  sq ft at a velocity of

$$\frac{15,000}{0.785 \times 3,600} = 5.3 \text{ fps} = \frac{15,000}{0.785 \times 5,280} = 3.6 \text{ mph}$$

## DIESEL FUELS

**Sources of Diesel Fuels.** There are at present and in the immediate future two main sources from which diesel fuels may be obtained, *viz.*, the virgin stocks in crude oils and the cycle stocks from catalytic cracking operations. The use of virgin stocks from crude has the advantage of higher cetane numbers but the disadvantage of being in competition with domestic heating-oil burners and with cracking units for production of high-quality motor gasolines. The use of cycle stocks suitably prepared for diesel fuel has the advantage of economic supply together with minimum fuel consumption in gallons per brake-horsepower-hour. On this basis, it is desirable to

Table 7-30. Specific Volume of Petroleum Products, Completely Vaporized at 1 Atm Pressure<sup>1</sup>

Gravity		Temp, deg F								
Deg API at 60°F	Sp gr at 60°/60°F	60	100	200	300	400	500	600	800	1000
Volume of vapor, cu ft/lb										
20	0.9340	..	...	....	....	.		1.8	2.1	2.5
25	0.9042	..	...	....	....		2.2	2.4	2.9	3.4
30	0.8762	...	...	....	....	2.5	2.8	3.1	3.6	4.2
35	0.8498	...	..	..	2.7	3.0	3.4	3.7	4.4	5.1
40	0.8251	.	.	2.7	3.1	3.5	3.9	4.3	5.2	6.0
45	0.8017	.	2.6	3.1	3.6	4.0	4.5	5.0	5.9	6.9
50	0.7796	2.8	3.0	3.5	4.0	4.6	5.1	5.6	6.7	7.7
55	0.7587	3.1	3.3	3.9	4.5	5.1	5.7	6.3	7.4	8.6
60	0.7389	3.4	3.6	4.3	4.9	5.6	6.2	6.9	8.2	9.5
65	0.7201	3.7	4.0	4.7	5.4	6.1	6.8	7.5	8.9	10.4
70	0.7022	4.0	4.3	5.1	5.9	6.6	7.4	8.2	9.7	11.2
75	0.6852	4.3	4.6	5.5	6.3	7.1	8.0	8.8	10.5	12.1
80	0.6690	4.6	5.0	5.9	6.8	7.6	8.5	9.4	11.2	13.0
85	0.6536	4.9	5.3	6.3	7.2	8.2	9.1	10.1	12.0	13.8
90	0.6388	5.3	5.7	6.7	7.7	8.7	9.7	10.7	12.7	14.7
95	0.6247	5.6	6.0	7.1	8.1	9.2	10.3	11.3	13.5	15.6
100	0.6112	5.9	6.3	7.5	8.6	9.7	10.8	12.0	14.2	16.5
110	0.5859	6.5	7.0	8.2	9.5	10.8	12.0	13.2	15.7	18.2
120	0.5626	7.1	7.7	9.0	10.4	11.8	13.1	14.5	17.3	20.0
130	0.5411	7.7	8.3	9.8	11.3	12.8	14.3	15.8	18.8	21.8
140	0.5212	8.4	9.0	10.6	12.2	13.8	15.4	17.1	20.3	23.5
150	0.5027	9.0	9.7	11.4	13.1	14.9	16.6	18.3	21.8	25.2
Volume of vapor, cu ft/gal										
20	0.9340	.	.	.	.	..	17	14	17	19
25	0.9042	.	.	.	.	..	17	18	22	25
30	0.8762	..	..	..	19	18	20	22	27	31
35	0.8498	..	..	..	19	21	24	26	31	36
40	0.8251	.	.	19	21	24	27	30	36	41
45	0.8017	.	18	21	24	27	30	33	40	46
50	0.7796	18	19	23	26	30	33	36	43	50
55	0.7587	19	21	25	28	32	36	39	47	54
60	0.7389	21	22	26	30	34	38	42	50	58
65	0.7201	22	24	28	32	37	41	45	54	62
70	0.7022	23	25	30	34	39	43	48	57	66
75	0.6852	25	27	31	36	41	46	50	60	69
80	0.6690	26	28	33	38	43	48	53	63	72
85	0.6536	27	29	34	39	44	50	55	65	75
90	0.6388	28	30	36	41	46	52	57	68	78
95	0.6247	29	31	37	42	48	53	59	70	81
100	0.6112	30	32	38	44	50	55	61	72	84
110	0.5859	32	34	40	46	53	58	65	77	89
120	0.5626	33	36	42	49	55	61	68	81	94
130	0.5411	35	38	44	51	58	64	71	85	98
140	0.5212	36	39	46	53	60	67	74	88	102
150	0.5027	38	41	48	55	62	70	77	91	106

<sup>1</sup> Thermal Properties of Petroleum Products, NBS (U.S.) Misc. Pub. 97, 1933.

Table 7-31. Specifications for Diesel Fuel Oils

Test	ASTM methods	Grade of diesel fuel					U.S. Navy specification 7-Q-2c
		1-D	3-D	4-D	5-D	6-D	
		Limit					
Flash point (deg F), min.....	D39-36	115 <sup>a</sup>	150 <sup>a</sup>	150 <sup>a</sup>	150 <sup>a</sup>	150 <sup>a</sup>	150
Water and sediment (max per cent by volume).....	D96-35	0.05	0.1	0.6	1.0	2.0	0.05
Viscosity, seconds Saybolt Universal at 100°F:							
Min.....	D88-36	35	35	....	.	..	35
Max.....	D88-36	50	70	250	.	..	45
Saybolt Furol at 122°F, max...	D88-36	...	..	..	100	300	
Carbon residue (per cent by weight), max.....	D189-36	0.2	0.5	3.0	6.0	.	0.2
Ash (per cent by weight), max...		0.02	0.02	0.04	0.08	.	0.01 <sup>a</sup>
Pour point (deg F), max <sup>b</sup> .....	D97-34	1.5 <sup>c</sup>	1.5 <sup>c</sup>	2.0 <sup>c</sup>	2.0 <sup>c</sup>	.	1.0
Alkali and min acid.....	D188-27T	None	None	None	None		
Ignition quality: <sup>d</sup>							
Cetane No., delay method, min.....	..	45	35	30	.	.	f
Diesel index No., min.....	..	45	30	20	.	..	45
Viscosity-gravity No., max.....	.	0.86	0.89	0.91	.	.	
Boiling-point-gravity No., max.....	.....	188	195	200	.	.	
Corrosion at 212°F copper strip ..	<sup>e</sup>				.	..	Negative
90 per cent distillation temp (deg F), max	D86-35	...	..	.	.	..	675

<sup>a</sup> Minimum flash point, as stated or as required by local fire regulations, Fire Underwriters, or state laws.

<sup>b</sup> Lower pour points may be specified whenever required by local temperature conditions to facilitate storage and use, although it may be necessary to waive minimum viscosity specified for oils 1-D and 3-D if pour point should be less than 10°F.

<sup>c</sup> Sulphur content, so far as known, does not affect combustion characteristics. The limits suggested are for engines in intermittent service.

<sup>d</sup> The values are equivalent within limits of error of the test methods used. As the correlations between indexes and between any index and engine operation are not completely established as yet, these values should be used in an approximate way only.

<sup>e</sup> Federal specifications VV-L-791a, Method 542.1.

<sup>f</sup> Although specifications include diesel index number, the right is reserved to require a minimum cetane number of 45 if the oil fails to exhibit satisfactory ignition quality in use.

<sup>g</sup> Federal specifications VV-L-791a, Method 530.31.

divorce ignition quality from the inherent properties of the diesel fuel.<sup>1</sup> To this end, current research is being directed toward the development of additives which, after the fashion of the lead compounds in motor gasoline, will improve ignition without impairing other burning characteristics. Such a development would have a further very important advantage of lightening the weight of diesels as a secondary result of the lower compression requirements for operation from cold starts.

**Diesel** fuel varies widely in its characteristics, ranging from light distillates, which are practically heavy kerosenes, to residual fuels or crude oils, which are used in a few instances. The API gravity ranges from (approximately) 40 to 17.5° at 60°F. This wide range of fuel results from the numerous designs of engines, not all of which can use any fuel having characteristics within these limits.<sup>2</sup>

The following classification by ASTM<sup>3</sup> suggests fuels that are suitable for different classes of engines:

<sup>1</sup> PINKERTON, R. D., "Diesel Fuel Oils," p. 45, ASME, 1948.

<sup>2</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 812, McGraw-Hill Book Company, Inc., New York, 1941.

<sup>3</sup> Committee Reports, *Proc. ASTM*, vol. 38, Part I, pp. 398-399, 1938.

**Grade 1-D** is suggested for mechanical (solid) injection engines of the high-speed type, in general, for engine speeds over 1,000 rpm.

**Grade 3-D** is suggested for mechanical (solid) injection engines of the medium-speed type, in general, for engines with speeds from 360 to 1,000 rpm.

**Grade 4-D** is suggested for air-injection engines, both two- and four-stroke-cycle types, with speeds not over 400 rpm. It can be used for mechanical (solid) injection engines of large bore (over 16 in.) and speed under 240 rpm.

**Grade 5-D** is suggested for air-injection engines with speeds under 240 rpm.

**Grade 6-D** is not regularly used as a diesel fuel and is not recommended unless approved by the engine manufacturer.

The U.S. Navy specifications 7-0-2c (Aug. 1, 1936) given in Table 7-31 illustrate the requirements of a high-grade fuel that will give reliable performance in almost any engine.

**Table 7-32. Gasoline Specifications**  
(ASTM D439-37T)

Test	ASTM method	Type A	Type B	Type C
Distillation temp, max deg F:	D86-35			
10 per cent evaporated .. . . .	..	W-140, F-149, S-158		167
50 per cent evaporated. . . . .	..	284	257	284
90 per cent evaporated .. . . .	..	392	356	392
Residue, max per cent .. . . .	..	2	2	2
Vapor pressure max psi at 100°F.....	D323-37T	W-13.5, F-11.5, S-9.5		
Octane No., min. . . . .	D357-37T	67 or 75 <sup>a</sup>	67 or 75 <sup>a</sup>	45 <sup>a</sup>
Corrosion .. . . .	D130-30	Passes	Passes	Passes
Gum, max, mg/100 ml. . . . .	D381-36	7 <sup>b</sup>	7 <sup>b</sup>	7 <sup>b</sup>
Sulphur .. . . .	D90-34T	<sup>c</sup>	<sup>c</sup>	<sup>c</sup>

W, F, S, = seasonal variations, approximately winter, fall, and summer. Temperature and vapor pressure specified depends upon atmospheric temperature expected.

<sup>a</sup> Octane number to be agreed upon between purchaser and seller. As of 1938:

75 octane number is minimum for premium-priced gasolines

67 octane number is minimum for regular-priced gasolines

45 octane number is minimum for third grade gasolines

<sup>b</sup> Gum requirements apply to base stock if gasoline contains added nonvolatile material.

<sup>c</sup> Technical data not adequate for general specifications. Government specifications for gasoline, VV-G-101a, and motor fuel, VV-M-571a, both require 0.10 per cent sulphur.

## CHAPTER 8

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### LIQUID FUELS OTHER THAN THOSE DERIVED DIRECTLY FROM CRUDE PETROLEUM

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## COAL-IN-OIL FUELS<sup>1</sup>

(Commonly Known as Colloidal Fuels)

Coal-in-oil fuels, commonly known as "colloidal fuels," are usually a mixture of up to about 43 weight per cent of finely ground coal suspended in fuel oil.

The impetus to research on coal-in-oil fuels originated within the coal industry in an effort to find additional outlets for hard-to-move fine sizes and low-quality coals; more recently, oil interests have become interested because of the potentiality of "stretching" short supplies of certain grades of fuel oil through admixture with coal.

Although admixtures of coal and oil are commonly called "colloidal fuels," the particles are much larger than true colloidal material, and it would thus appear that they are only in a state of minute suspension even though, under certain conditions, finely divided coal may assume the colloidal state as suspended in oil.

While the change from one state of suspension to another is continuous and therefore not sharply defined, Zsigmondy, as reported in Perry's "Chemical Engineers' Handbook," classifies solutions of solid particles as follows:

**Suspensions.** Particles coarser than 0.1 micron in mean diameter.

**Colloidal Solutions.** Particles under 0.1 micron and over 0.001 micron in mean diameter.

**True Solutions.** Particles under 0.001 micron in mean diameter.

As the particle size corresponding to 200 Tyler mesh is 74 microns and that corresponding to 325 Tyler mesh 44 microns, it is obvious that coal could not be ground sufficiently fine for true colloidal solutions. It is thus in a state of fine suspension in coal-in-oil fuels.

Table 8-1. Tyler Screen Scale as Related to Particle Size<sup>a</sup>

Meshes per in . . . . .	10	20	35	48	65	100	150	200	325
Micron scale . . . . .	1,650	830	420	300	220	150	110	74	44

<sup>a</sup> See Chap. 14 for full table.

**Field experience** with coal-in-oil fuels is principally limited to research and test data as, even in such few cases of sustained use as are known, published records are meager.

Examples of full-scale and experimental use include the Standard Oil Company's disposal of a large amount of high-ash anthracite by mixing with oil (at Brooklyn); transatlantic tests of presumably low-grade bituminous coal admixed with oil on the steamships *Scythia* and *Berengaria* of the Cunard Line; full-scale commercial and industrial boiler tests by the U.S. Bureau of Mines and the Atlantic Refining Co. at Philadelphia; studies of the Submarine Defense Association under the chairmanship of Linden W. Bates, including tests of Pocahontas bituminous coal and Texas oil on the yacht *Gem* in Long Island Sound; extensive mixing tests of the Koppers Co.; and comprehensive experiments of Kansas State College at Manhattan, Kans., in cooperation with the Pittsburgh and Midway Coal Mining Co.

### Advantages and Disadvantages of Coal-in-oil Fuel

While leading investigators disagree to some extent as to the potential advantages and disadvantages of coal-in-oil fuels, the items most frequently cited include

<sup>1</sup> General references: (1) JONNARD, AIMISON, Colloidal Fuel Development for Industrial Use, *Bull.* 48, Kansas State College, Manhattan, Kans., January, 1946. (2) BARKLEY, HERSBERGER, and BURDICK, "Laboratory and Field Tests on Coal in Oil Fuels," Pittsburgh meeting, Fuels Division ASME, and Coal Division AIME, October, 1943. (3) SCHROEDER, W. C., Uses of Mixtures of Oil and Coal in Boiler Furnaces, *Mech. Eng.*, vol. 64, No. 11, pp. 793-798, November, 1942.

**Advantages as Compared with Oil**

1. They may be cheaper than oil in many localities.
2. Their widespread use would assist in the conservation of petroleum resources, and in direct proportion to the percentage of coal used.
3. They are heavier than oil and therefore permit fires to be extinguished more easily with ordinary fire-fighting equipment.
4. Their heating value on a volume basis is higher than that of either coal or oil alone.

**Advantages as Compared with Coal**

1. They may be handled like oil in pipes and pumps (with allowance for increased power and sedimentation).
2. They enable better use of storage space than does coal.
3. Their use would eliminate the danger of spontaneous combustion.
4. They have lower ash and moisture contents than coal.
5. Their use would permit more ready disposal of such fuels as low-rank coals, lignite, and fine sizes.
6. They can be burned automatically in simple oil-burning equipment.

**Additional Advantages for Marine Use**

7. Coal is more universally distributed, and shipping difficulties, for at least that part of the fuel, might be decreased.
8. The additional heat content on a volume basis of some 1 to 4 per cent over oil alone allows a proportionate saving in bunker space.
9. Coal-in-oil fuel, being heavier than water, would not float on the surface to endanger survivors in disasters.

Pulverized coal has some of these advantages, but coal-in-oil fuels would probably be more adaptable to small plants and in cases where it is necessary to store or transport the prepared fuel.

Although, as for conventional fuel use in multiboiler plants, it might sometimes be difficult to justify admixing coal and oil as compared with the more simple expedient of burning coal in some boilers and oil in the others, this would not necessarily apply in many applications where a liquid fuel has distinct advantages. Outstanding examples are railroad and marine use, cracking coils and pipe-still furnaces of oil refineries, metallurgical furnaces, open-hearth furnaces of the steel industry, and reverberatory furnaces in copper melting.

Coal-in-oil fuels may also have commercial potentialities other than as fuels such as for chemical raw materials. There is an increasing use of coal as a raw chemical, and it can be handled most efficiently by suspending it in a liquid such as oil.

**Disadvantages of Coal-in-oil Fuels**

1. (In marine use) Tank connections are arranged for a lighter-than-water fuel. Substitution of heavier-than-water colloidal fuel might necessitate extensive changes of such pipes as the drains, cleanouts, etc.
2. (In marine use) During a war any increase in ash content of a fuel is undesirable since it leaves a trail or slick on the surface of the water. The higher the ash content the longer it is visible, and the more easily it may be followed by enemy vessels.
3. According to John Van Brunt (Combustion Engineering Co.), the use of coal-in-oil fuel may result in greatly increased deterioration of refractory-lined furnaces. Thus the use of waterwalls, etc., may be necessary.
4. The increased ash content as compared with oil will be a disadvantage in any case and may be the deciding factor in some nonboiler uses.

**General Characteristics of Coal-in-oil Fuels**

The characteristics of coal-in-oil admixtures are apparently quite different from those of oil alone. Mixtures containing 40 per cent coal will be as much as 10 per



cent heavier in weight per unit of volume; they will be four to eight times as viscous, depending on temperature; they are more abrasive; and any settling out of the coal may result in pastelike accumulations. Flash and fire temperatures remain virtually the same as with oil and unchanged with different mixtures.

### Selection of Fuels for Admixing

According to Barkley, Hersberger, and Burdick, "If the criteria from a standpoint of stability and handling of a satisfactory coal-in-oil fuel are (1) high degree of stability at normal temperature, (2) sufficient temperature at elevated temperatures to permit handling in conventional oil-burning equipment, and (3) reasonable viscosity, the results of this work point toward a 40 weight per cent of -230-mesh bituminous coal dispersed in No. 6 fuel oil. For practical purposes, the coal specification sizing should be set at 98 to 99 per cent passing a 230-mesh screen, and the limiting oil properties at 12 to 14.8° API gravity at 60°F and 55 to 70 Furol viscosity at 122°F."

Anthracite fines or culm offer an economic source of solid fuel. On the other hand, anthracite has several characteristics that make it less desirable than bituminous coal. It is high in ash, difficult to grind, and slow to ignite. Stabilization of an anthracite-oil mixture may be more difficult than an oil-bituminous mixture, because the bituminous coal contains organic matter which tends to dissolve or be wet by the oil or stabilizing agent, while anthracite is relatively pure carbon.

**Percentage of Coal in Mixture.** Coal-in-oil mixtures develop greater stabilization with greater solids content. With 200- to 230-mesh material, no useful or dependable stability is obtained below about 33 volume per cent of coal, while worthwhile rigidity or stability starts at about 40 weight per cent concentration.

**Table 8-2. Changes in Viscosity of Coal-in-oil Mixtures at 170°F<sup>1</sup>**

Coal, per cent	Oil, per cent	Viscosity, seconds*
0	100	81
10	90	92
20	80	112
30	70	150
40	60	260
50	50	1,600

<sup>1</sup> BUTCHER, ALFRED, Gulf Oil Corp., Pittsburgh, *Mech. Eng.*, April, 1943, p. 279.

\* Saybolt Furol.

On the other hand, viscosity increases with increases in the percentage of coal in suspension. Beyond about 43 weight per cent of coal, this increase is so rapid as to affect pumping seriously.

Therefore, for practical purposes, the weight percentage of coal in a coal-in-oil admixture lies between 33 and 43 per cent, with most current experimentation indicating a preference for the latter figure.

**Pulverization of the Solid Fuel.** Fine grinding of the solid fuel simplifies the problem of stabilization but tends to increase the viscosity of the mixture to complicate the pumping problem.

As has been shown, Barkley *et al.* consider 98 to 99 per cent 230 mesh to be an optimum bituminous-coal size. Jonnard gives 200 mesh as the "required size" for the coal component of coal-in-oil fuels. Unless additives to increase the fluidity are used, there is a rapid rise in viscosity between the coal sizes of 200/230 and 230/325 mesh (U.S. Standard screen). In all past work this has proved to be the limiting factor because of increased power for pumping and similar handling. However, proponents of finer grinding are engaged in research to develop the advantages of much finer mesh coal. It is possible that this will be accomplished through the use of additives or wetting agents to increase the fluidity of the mixtures.

Figure 8-1 combines the stability-sizing curve and the viscosity-sizing curve of Barkley, Hersberger, and Burdick to show this opposing relationship. It is seen that, as the size of the coal particles decreases, stability increases; as the size decreases, viscosity increases. Thus, as the particles become larger, stabilizers become more necessary and/or the material must be used more quickly after it is mixed. As the

particles become smaller, pumping facilities must either be expanded or additives used to increase the fluidity of the admixture.

Local choice must be made between the use of stabilizers, immediate use after mixing, mechanical stirring in storage, and continuous circulation, or additives to increase fluidity.

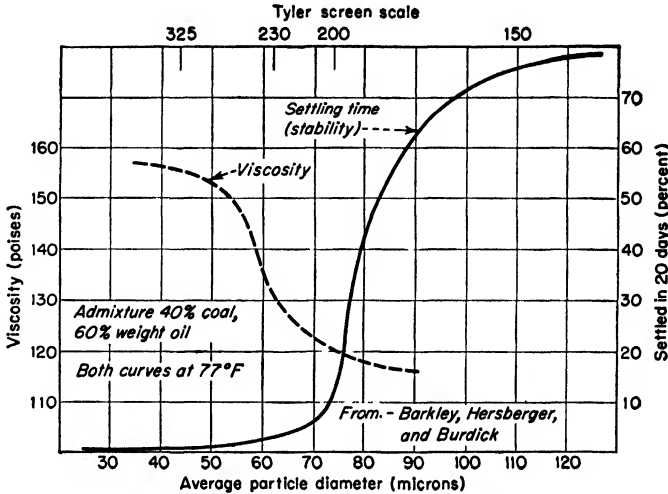


Fig. 8-1. Opposing effect of particle size on viscosity and stability of suspension.

In preparing the fine coal, the effect of the maximum-sized coal on the stability of suspension is important. The presence of even small quantities of oversized particles has been found to increase the stability of suspension materially.

### Mixing and Storing Coal-in-oil Fuels

Mixing equipment used successfully by Jonnard consisted of an open tank equipped with a high-speed agitator propeller.

He reports that the formation of a vortex on the surface of the liquid, into which the coal could be poured while mixing, was absolutely necessary. When the coal was fed too fast or accumulated on the oil surface for any other reason, agglomerates were formed which were not readily dispersed by further mixing. He located the agitator near the surface of the oil in order to create this vortex.

At 1.7 cents per kw-hr, Jonnard calculates the cost of power for mixing to be less than 1 cent per ton of finished fuel.

Barkley, Hersberger, and Burdick fed coal from a continuously filled funnel into the suction line of the circulating pump. The coal, as controlled by a hand valve, was allowed to flow slowly into the stream of oil on its way to the pump. The coal was fed at a rate of about 1,500 lb per hr until the required amount had been placed in the 5,000 to 7,000 gal of oil, after which circulation at a rate of about 9,000 gph was continued for about 12 hr before the mixed fuel was considered ready for use.

Coal-in-oil mixtures should be kept in motion. Storage tanks should be designed, baffled, or equipped with agitators so that no lodgment of the coal dust can take place in corners or dead spots. The admixture should be continuously circulated in the piping system, using long-radius bends for turns.

Mixing tanks are usually equipped with steam coils to maintain proper temperatures during mixing and operation. Oil temperatures during mixing usually range

from 75 to 130°F. Jonnard reports that, whereas fuel oil alone was best handled between 200 and 230°F, the optimum temperature for handling coal-in-oil fuel was 180°F. As this is higher than some temperatures cited, it should be noted that overheating sometimes tends to cause some clogging in the burners and promotes an accumulation of "paste" in the lines, tanks, etc.

#### Additional Factors of Stability in Suspension

While actual conditions for settling in suspension are complex, the following general rules have been noted:

1. If the coal is ground and mixed in the plant in which it is to be burned, the storage time can be held to a minimum, and stability will not be a problem.

2. Stability may be somewhat disregarded by equipping storage tanks with circulating pumps or, in the case of smaller tanks, by periodic stirring. Such methods require considerable power, but it is often possible to use the same motors for both agitation and transportation by pumping.

3. Certain coal-in-oil mixtures produce fuels which remain stable for months without any additional treatment. The settling tendency is directly proportionate to (a) the size of the coal particles, (b) the difference in the densities of the oil and coal, and (c) the temperature of the fuel. The settling tendency is inversely proportionate to (d) the viscosity of the oil, and (e) the concentration of the coal. Other factors, such as the presence of electrical charges on the solid particles, may also have an important effect.

4. The effect of the physical properties of the coal and oil on the stability of suspension is important. The use of an oil with high specific gravity increases stability, the best oils in this respect being cracked fuel oils. The use of oils of high viscosity also increases stability, but there is an upper limit beyond which pumping costs become prohibitive, especially since the addition of coal may be expected to increase the viscosity further. Coal-in-oil fuels made with No. 6 fuel oil can be handled in ordinary oil-handling equipment; more viscous oils would probably require changes such as increasing the temperature of the fuel or the diameter of the pipes.

#### Stabilizers, or "Fixateurs," for Increasing Stability

5. The use of stabilizers to improve suspension has received a considerable amount of attention. The general conclusion is that practically all the many methods and substances proposed are unsatisfactory. Some simply fail to stabilize; others require extensive and expensive amounts of agents; others require extremely fine grinding at considerable added expense; and still others form a gel which is difficult to pump and tends to clog.

As a result, it is a consensus that, with careful attention to a selection of fuels, pulverization, mixing, and storage, stabilizers can and should be avoided in most cases.

Jonnard, having tested 148 stabilizing agents, concluded that spent alkylation acid<sup>1</sup> was the only one with commercial possibilities.

Jonnard notes that the spent acid is more effective if the oils have been contacted previously with solid sodium hydroxide pellets.

With light oils, such as gas oil, spent acid is ineffective, probably because of insolubility, No. 5 oil being the lightest with which it was effective. The only agents which Jonnard found effective with light oils formed gels, were difficult to pump, and required large expensive quantities. He further notes that in heavy oils no stabilizers were needed.

The most fluid oil in which spent acid was effective had a viscosity of 186 seconds

<sup>1</sup> A spent acid catalyst waste product of the petroleum industry resulting from the chemical reaction of butane and isobutylene during the preparation of isooctane for aviation gasoline.

Saybolt Furol at 122°F but has a gravity of 11.4 API. The addition of as little as 0.1 to 0.2 per cent of spent acid increased viscosity considerably but amounts smaller than 0.1 per cent were not effective. Industrially, it would probably be necessary to add the acid to the oil in a fine spray because of its low solubility and its being heavier than the oil.

Barkley, Hersberger, and Burdick reported that "of all the stabilizers studied, the addition of 1 to 1.5 per cent of sulphuric acid to the coal surfaces before mixing with the oil was found to give the best results." Hersberger, however, concludes that stabilizers are unnecessary if the coal is properly ground and mixed.

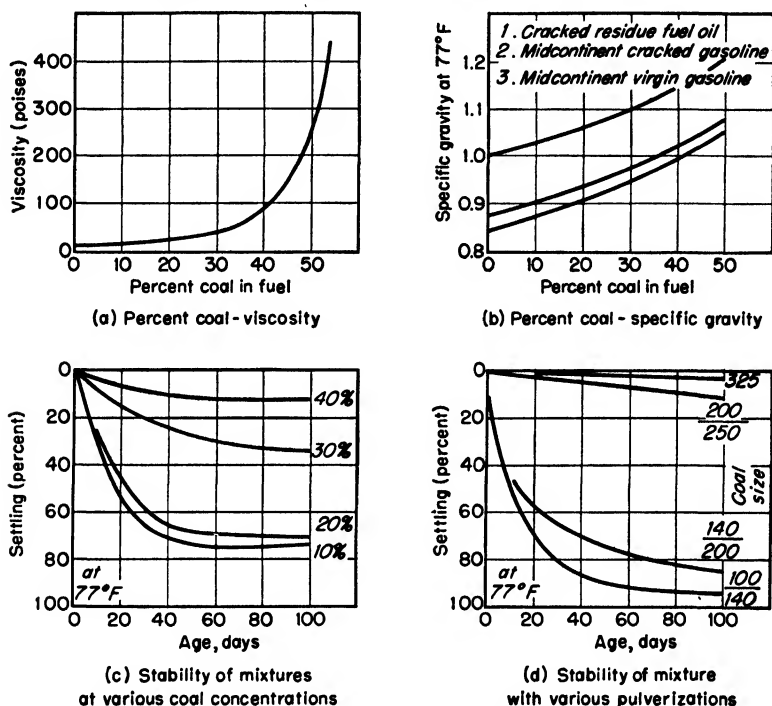


FIG. 8-2. Some general characteristics and trends of coal-in-oil fuels. (Curves shown in this group are intended to show trends only and are not accurate as to specific figures.)

Schroeder cites experiments showing that coal tar is very effective because at temperatures of from 250 to 300°C the coal is peptized, *i.e.*, partly dissolved and partly suspended, by coal-gas tars, water-gas tars, and particularly by middle and fraction oils from tar distillation. Relatively high percentages of tar, 5 to 20 per cent, are needed, and the demand for tar would therefore exceed the supply if colloidal fuels should become popular.

### Practical Operation in Boilers

For practical use in boilers, all investigators have recommended the use of steam-atomizing burners and look upon mechanical atomization with considerable doubt.

The burners should be tapped into a circulating system, using proper nonclogging regulating valves for fuel-quantity adjustment.

Van Brunt warns that refractory furnaces may not hold up under coal-in-oil fuels and recommends either waterwalls or reduced rating.

Neither Jonnard nor Barkley, Hersberger, and Burdick experienced any difficulty in burning up to 43 weight per cent of coal-in-oil fuel in standard oil-burner settings. Jonnard reported some slag on the tubes, which was loose and soon fell off; and he further noted a softer somewhat dusty flame which filled the furnace more completely and without the cutting or impinging effect of certain fuel oils as burned alone. He felt that boiler efficiencies would equal or better those of either fuel oil or pulverized coal and cited a test on 40 per cent coal, coal-in-oil fuel at an average boiler rating of 130 per cent at an efficiency of 75.8 per cent.

Barkley, Hersberger, and Burdick report comparative tests of No. 6 fuel oil and three batches of 40 per cent coal-in-oil fuel as shown in Table 8-3. The boiler was a 151-hp long-drum water-tube Babcock & Wilcox as operated on a regular steaming run. The operators obtained slightly lower boiler efficiencies with coal-in-oil fuels than with oil; about 79.5 to 80.5 with coal-in-oil as against 81.2 per cent with oil alone. However, this difference was small enough to be within the limits of test errors and is thus not finally conclusive. No operating difficulties were reported; the flame responded smoothly to changes in the boiler load; smoke could be controlled as with oil, except when starting cold; and CO<sub>2</sub> could be controlled to any desired point without CO. Two-thirds more atomizing steam was required than with oil alone. Troubles from ash were negligible, although fly ash should be removed every 8 hr. While no settling or clogging was noted in the lines, there was some clogging in the screens,

Table 8-3. Comparative Boiler Tests on Oil and Coal-in-oil Fuels<sup>1</sup>

Test No	1	2	3	4
Make and type of: Boiler Superheater Burner	B. & W. longitudinal drum B. & W convection Best, steam-atomizing burner			
Total heating surface	1,792 sq ft			
Fuel type	No. 6 oil	Coal-in-oil		
Per cent coal.	0	39 4	39 7	39 5
Btu/lb	18,380	16,820	16,670	16,960
Sp gr	0 982	1 082	1 094	1 083
Ash, per cent.		2 4	3 1	1 8
Carbon dioxide, per cent	12 8	12 2	13 9	14 7
Temp, deg F:				
Flue gases	457	480	476	455
Fuel in tank	75	81	88	84
At pump.	60-70	85-125	75-110	70-95
Leaving heater,	180-200	160-180	180-195	150-170
At burner	163	154	163	142
Duration of test, hr	192	144	120	120
Dry fuel per hour, lb.	347	380	389	384
Fuel/cu ft furnace/hr, lb	0 63	0 70	0 72	0 70
Per cent steam used for atomizing	1 8	3 2	2 7	3 2
Refuse in furnace, per cent dry fuel	.....	0 4	0 8	0 3
Dust entering stack, per cent dry fuel		1 9	2 3	1 2
Rate of heat absorption, Btu.	14,930	13,420	13,340	13,670
Rating developed, per cent	103	101	103	104
<b>Heat Balance</b>				
Heat loss H <sub>2</sub> O from hydrogen, per cent.	6.4	5.7	5.6	5.6
Heat loss dry flue gases, per cent.	9.0	10.3	8.9	8.1
Efficiency, per cent	81.2	79.8	80.0	80.6

<sup>1</sup> Condensed from BARKLEY, HERSBERGER, and BURDICK.

control valves, and meters, and occasional slight clogging at the burner tips. Some wear was noted at the burner tips and in the rotary pump. The capacity of the rotary pump dropped about 30 per cent. While the reciprocating pump capacity also dropped, it was not measured.

Attempts by Barkley *et al.* to burn coal-in-oil fuel in two 20 and 90 gph rotary-cup commercial burners were not so successful, principally because of pumping and ignition difficulties and carbon accumulations in the cup.

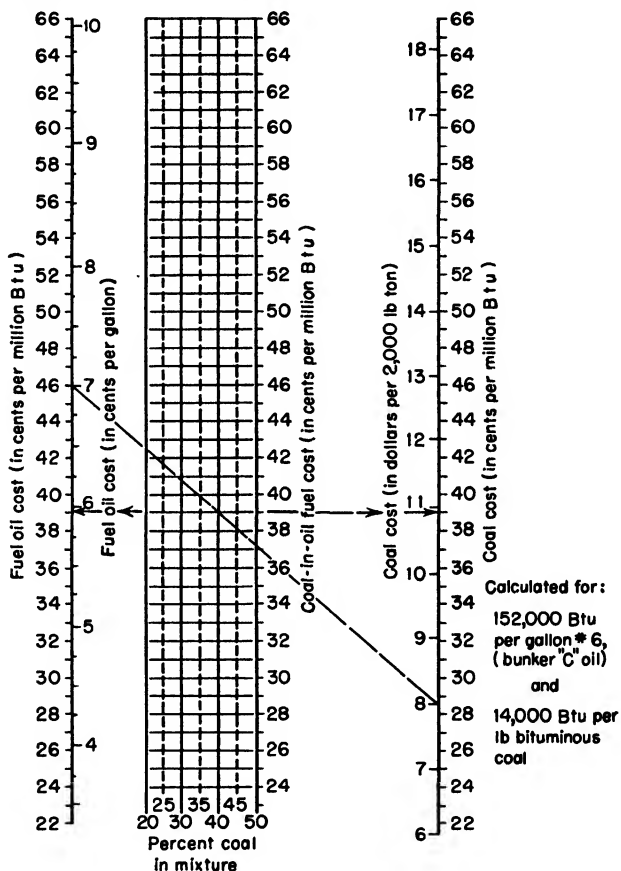


FIG. 8-3. Economic chart for coal-in-oil fuel.

#### Economics of Coal-in-oil Fuel

Figure 8-3 permits a direct comparison of the resultant cost of coal-in-oil fuels, using various weight percentages of coal in the admixture, and with various priced coal and oil.

A line drawn between the cost of oil on the left-hand scale and the cost of coal on the right-hand scale will intersect the center family of lines, which represent the per cent of coal in the admixture as marked at the bottom, at points corresponding to the resultant coal-in-oil fuel costs.

**Example:** As illustrated by the very light dash lines, a line between oil at 7 cents a gallon and coal at \$8 a net ton intersects the 40 per cent coal-in-oil line at 39 cents per million Btu.

This, then, is the cost of the admixture. This resultant cost may be further compared with oil by extending the point of intersection horizontally to the oil scale, as shown by the left arrows, where it is seen that 39-cent fuel is equivalent to 5.95-cent oil, as compared with the 7-cent oil used in the mixture. Similarly, by extending the point of intersection horizontally to the right, it is seen that the admixture is equal in cost to \$10.95 per ton coal. As the cents per million Btu are all on the same horizontal plane, a ruler placed horizontally permits a direct comparison of oil and coal at any price level.

This chart takes into consideration only the raw material at fixed heat values of 152,000 Btu per gal for fuel oil and 14,000 Btu per lb for coal. In cases where more accurate or more inclusive cost comparisons are desired, the following formula by F. W. Godwin of the Armour Research Foundation will be useful:

Cost of coal-in-oil fuel, cents per million Btu

$$= \frac{K(P_c + C_g) + [(1 - K)/d]47.62P_o + C_m}{0.00002[KH_c + (1 - K)H_o]}$$

where  $P_c$  = cost of coal including freight, dollars per ton

$P_o$  = cost of oil including freight, dollars per bbl

$C_g$  = cost of grinding and preparing the coal, dollars per ton

$C_m$  = cost of mixing and stabilizing the coal-in-oil fuel, dollars per ton of finished fuel

$H_c$  = heating value of coal, Btu/lb

$H_o$  = heating value of oil, Btu/lb

$K$  = tons of coal used per ton of finished fuel

$d$  = density of the suspending oil, lb/gal

Fixed charges of the buildings, grounds, and storage facilities should be added to another term added to the numerator, or they can merely be added to the cost of mixing,  $C_m$ .

### PETROLEUM PRODUCTS FROM SHALE<sup>1</sup>

The extraction of oil from shales is not a new concept. The French shale-oil industry dates from 1838, the Scotch from 1850. The Japanese fueled part of their navy with shale oil during the Second World War. Substantial shale-oil industries operate today in Scotland, Sweden, South Africa, Australia, France, Spain, and perhaps Estonia and Russia.

While oil shale is found in several parts of the United States, the richest beds are located in the vicinity of the intersection of Wyoming, Utah, and Colorado (see Fig. 8-4).

By what are generally considered to be conservative estimates, the potential petroleum reserve contained in United States deposits of shale is at least 250 billion bbl. This is as compared with some 20 to 25 billion bbl of liquid-petroleum reserves in the United States.

In the United States the recovery of oil from shale is complicated by the fact that the containing rock, while generally called shale, is actually a marlstone, which is considerably harder than shale.

The great Athabaska tar sands of Canada, frequently confused with oil shales, are in reality quite different and should not be so classified.

**Nature of "Oil" Contained in Shale.** Oil does not exist in shale in the same form as the liquid crude oils; in fact, the substance contained in the pores of the United States marlstone, or "shale," is not even an oil, but a solid known as "kerogen."

**Kerogen** is a general term for organic matter that has been decomposed down to a certain point and then remained fixed. According to one theory, whereas petroleum was formed from minute animal and vegetable organisms trapped in silt at the bot-

<sup>1</sup> From *The Lamp*, Standard Oil Co. (New Jersey), vol. 31, No. 1, pp. 27-31, January, 1949.

tom of salt-water seas, kerogen, in this country, came largely from minute plants that were deposited at the bottom of fresh-water lakes.

Kerogen contains hydrocarbons in combination with sulphur, oxygen, and nitrogen. It can be cracked into an oil at temperatures of about 800°F. The chemical make-up of shale oil greatly complicates the refining problem to such a point that any widespread use of this material will probably necessitate entirely new refining methods, rather than the infinitely simpler mere substitution of shale oil for petroleum in present equipment.

Shale-oil molecules have a peculiar structure; they do not have enough hydrogen atoms to match their carbon atoms but instead have excessive quantities of unwanted elements, particularly sulphur, oxygen, and nitrogen, the last two of which are rarely found in petroleum. The result is that shale oil is unstable and therefore deposits gum, sludge, and sediment. It also has a disagreeable odor.

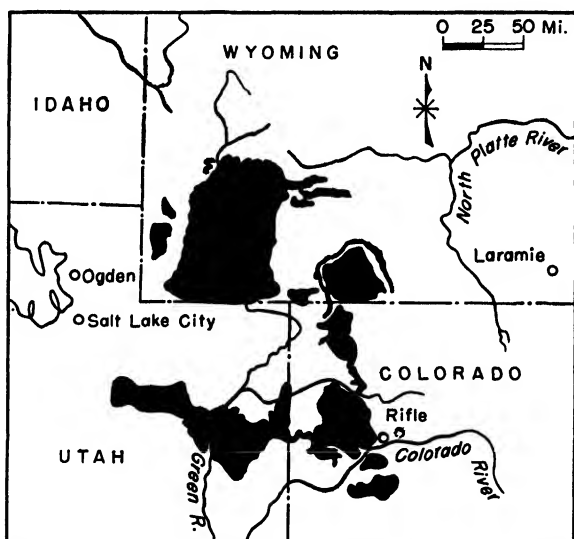


FIG. 8-4. Location of principal oil-shale fields of the United States. (*The Lamp*.)

In the opinion of Standard Oil Co. (New Jersey), one of several companies who are working in cooperation with the U.S. Bureau of Mines in an effort to solve this and similar problems, hydrogenation may prove to be the solution by facilitating the removal of both unwanted elements and the odor. If so, the resulting shale oil would be the equivalent of a high-quality petroleum crude, which can be readily converted to gasoline, diesel fuels, heating oils, and other standard petroleum products.

**Oil-shale Yield.** Engineers of the U.S. Bureau of Mines report that the yield from a ton of marlstone, or "shale," will vary from a few gallons to well over 50 gal. At present 30 gal per ton recoverable content is considered to be the minimum-yield material which can meet economic considerations. On this basis,  $1\frac{1}{2}$  tons of rock must be mined and handled per barrel of oil yield. Present estimates of mining cost to the portal of the Bureau of Mines experimental mine and refinery at Rifle, Colo., are currently less than 30 cents per ton of oil-bearing rock.

**Prospects for Oil Shale.** In general, the three following conditions must be met before shale oil can take its place beside standard fuels:



1. The cost of mining the ore must be made low enough so that it will be economically practical to handle the vast amounts of oil-bearing rock that will be needed.
2. An efficient and economic way must be found to extract the oil from the shale, undoubtedly in a continuous process.
3. Research must devise means of refining the crude shale oil into useful products in the price and quality range of petroleum products.

As neither hydrogenation nor the other necessary steps are cheap, it now seems quite definite that shale oil will cost more than liquid-petroleum fuel made from natural gas, but not necessarily more than a similar fuel made from coal. However, natural gas and coal are fuels in their own right; oil shales, underlying thousands of square miles in several parts of the country, are utterly wasted resources unless they can be converted into some such useful fuel.

## SYNTHETIC MOTOR FUELS

### Synthetic Motor Fuels<sup>1</sup> from Gases

Synthetic chemical compounds obtained from waste gases by pressure catalysis, hydrogenation, pyrolysis, polymerization, etc., constitute suitable replacement motor fuels. Much research is now being done on these processes; but, because of the rapidly changing status resulting from the flow of new data secured by the many investigators engaged in exploring the possibilities of these sources, very little accurate or stable information on yield or cost can be secured.

Not only is petroleum itself a very cheap raw material, with potentialities perhaps as great as those formerly possessed by coal tar, but waste refinery cracking gas and other refinery wastes; coal tar, water gas, and coke-oven gas; natural gas; and similar sources of paraffins and olefins are abundant, and all are susceptible of chemical treatment in several ways. Moreover, the products obtained by various methods of processing are frequently identical, although the respective percentages may vary. Besides these sources, the liquefaction of coal by hydrogenation and the distillation, or cracking, of creosote and tar by-products from wood or low-temperature coal distillation constitute potential sources of motor fuel.

Most of the synthetic fuels produced from waste gases are notable for high octane values, and many of them are similar to present gasoline fuels and therefore introduce no new problems in engine performance or design.

Two of the simpler processes of producing alcohols and alcohol derivatives from gas by synthetic methods have already reached commercial production. These are production of **methanol (wood alcohol)** by the catalytic synthesis of carbon monoxide and hydrogen, and the production of **ethanol** by absorption of ethylene in sulphuric or other mineral acids and subsequent hydrolysis. The respective cost of production of such synthetic alcohols is probably considerably below that of the alternate older processes of wood distillation and sugar fermentation.

**Amyl alcohol** is being produced commercially in the United States by the chlorination and hydrolysis of petane fractionated from natural gasoline.

**Isopropyl alcohol** has been commercially produced by acid absorption of propylene obtained from the overhead gas resulting from stabilized cracked petroleum.

**Acetone** has been made from the reduction of isopropyl alcohol, which in turn was derived from petroleum gases.

**Other alcohols or compounds** can be synthesized by using the same basic materials and equipment and by the same general process by variations in pressure and temperature or by percentage concentration.

Based on an estimated annual production of 300 billion cu ft of cracked gas, and a

<sup>1</sup> Motor Fuels from Farm Products, U.S. Dept. Agri., Misc. Pub. 327, p. 102, 1938.

yield of 5 gal of polymer gasoline per 1,000 cu ft of gas, about 1,500,000,000 gal of motor fuel might be obtainable from this source alone.

### Ethyl Alcohol as a Motor Fuel<sup>1</sup>

Many claims have been made as to the superiority or inferiority of alcohol as a motor fuel, with the subject remaining controversial at this date. On the basis of available combustible matter, gasoline is a better fuel for engines of present design than alcohol, since high-test gasoline may contain 135,000 heat units (Btu) per gal compared with only 84,425 for alcohol. The low absorption of water by gasoline, in contrast to the miscibility of water and alcohol, is a further advantage. However, certain physical characteristics of alcohol are more favorable. The relative advantages and disadvantages of both straight alcohols and various blends are discussed in detail in the reference cited.

In foreign countries where gasoline is in short supply, blends of from 5 to 25 per cent have been commercially used for several years. Advantages claimed include the high octane number of alcohol (99) and the high latent heat of vaporization (368 Btu per lb). As mentioned above, the Btu value (12,810 Btu per lb high heat value) is low as compared with gasoline to result in a specific fuel consumption for maximum power that is greater. Performance is essentially the same as gasoline, excepting that cold starting may be difficult. Troubles from increased corrosion and solvent action have been reported. Alcohol-gasoline blends tend to separate in presence of water, but the stability can be improved by the use of such blending agents as benzene, toluene, and the higher alcohols.<sup>2</sup>

### Methanol (Wood Alcohol)<sup>1</sup>

As a motor fuel, methanol is inferior to ethyl alcohol, since it yields only about 73 per cent (weight basis) of the net heat units of ethyl alcohol. Also, it has poorer blending qualities when used with gasoline. It has a higher latent heat of vaporization than ethyl alcohol and a lower boiling point. It requires less air for complete combustion and consequently has a higher volumetric efficiency. Under certain conditions, however, methanol may show better performance than ethyl alcohol. In special fuels, it has been used in quantities as high as 40 per cent of the fuel mixture, the cost being of secondary importance in such cases. It is used quite extensively as an ingredient of racing fuels.

### Foreign Use of Gasoline-Alcohol Blends

While the use of gasoline-alcohol blends in Europe was rather extensive, and usually compulsory before the Second World War, no attempt will be made to list the practice, since postwar information is not available and radical changes are therefore to be expected. As of 1938, the status in Central and South America was as follows:

**Cuba.** Motor blends were used but not required. Petroleum was plentiful, but authorities urged the extensive use of alcohol as a stimulus to the sugar industry.

**Panama.** An executive decree, effective in 1934, authorized the marketing of a mixture known as "alcoholina," but its use was not compulsory. The move was intended to benefit sugar-cane growers and was subsidized. Despite this, the cost of the fuel was high and its acceptance very poor.

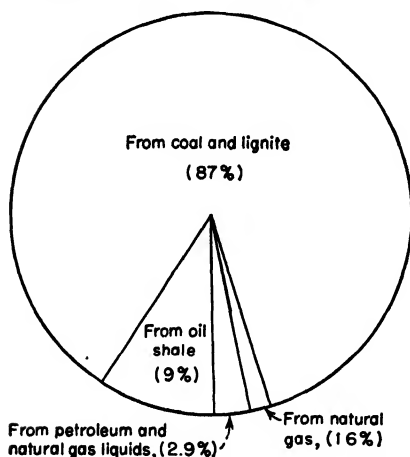
**Brazil.** No petroleum was produced in Brazil. In 1934, the government authorized the sale of 10 per cent blends, which was raised to 15 per cent in Rio de Janeiro in 1937. Difficulty was experienced in obtaining sufficient alcohol.

<sup>1</sup> *Loc. cit.*, p. 87. See also, Sulphite-liquor Alcohol in Sweden, on page 247.

<sup>2</sup> See Symposium on Motor Fuels, *Ind. Eng. Chem.*, September, 1936, pp. 1080-1112.

Table 8-4. Physical Properties of Alcohols, Hydrocarbons, and Miscellaneous Organic Substances<sup>1</sup>

Material	Mol. wt	Freezing point, deg F	Boiling point, deg F	Sp gr at temp shown, deg F	Latent heat of vaporization at temp shown, deg F g-cal/g	Heat of combustion, Btu/lb	Flash point, deg F	Octane No.
Acetone.....	58 05	-138	119	0.793 @ 68	134 74 @ 32	13,122	0	
Amyl alcohol	88 11	-109	280	0.814 @ 68	120 17 @ 268	16,236	104	
Butyl alcohol	74 08	-129	244	0.811 @ 68	141 00 @ 244	15,498	111	
Ethyl alcohol	46 05	-174	173	0.791 @ 68	236 00 @ 32	12,816	65	90 <sup>a</sup>
Methyl alcohol	32 03	-143	148	0.793 @ 68	284 00 @ 32	9,522	52	
Isopropyl alcohol	60 06	-129	180	0.786 @ 68	141 00 @ 180	14,256	67	
Aniline.....	93 06	21	364	1.039 @ 32	104 00 @ 32	15,678	160	
Diethyl ether....	74 08	-177	94	0.736 @ 32	94 00 @ 32	15,660	-52	
Gasoline, A-2 <sup>b</sup>	114 <sup>c</sup>	-60	115-389	0.738 @ 60	71 @ 250	20,250	0	48.4 <sup>d</sup>
Gasoline, B-2 <sup>b</sup>	115 <sup>c</sup>	-60	111-359	0.756 @ 60	70 @ 250	20,142	0	68 <sup>a</sup>
Gasoline, C-6 <sup>b</sup>	94 <sup>c</sup>	-60	122-316	0.712 @ 60	72 @ 250	20,394	0	76 <sup>a</sup>
Butane.....	58 08	-211	31	0.601 @ 32	91 5 @ 32	20,988	Gas	71 <sup>d</sup>
Cyclohexane....	84 09	44	177	0.797 @ 32	86 @ 32	20,070	-1	84 <sup>d</sup>
Benzol.....	78 05	42	176	0.900 @ 32	107 @ 32	18,018	6	88 <sup>d</sup>
Heptane ..	100 12	-131	205	0.700 @ 32	90 @ 32	20,664	25	0 <sup>d</sup>
Hexane.....	86 11	-140	156	0.677 @ 32	91 1 @ 32	20,700	0	23 5 <sup>d</sup>
Naphthalene ..	128 06	176	424	0.978 @ 32	75 5 @ 392	17,388	187	
Octane ..	114 14	-70	258	0.719 @ 32	89 4 @ 32	20,608	63	-13 <sup>d</sup>
Pentane ..	72 09	-202	97	0.645 @ 32	93 15 @ 32	20,808	0	57 5 <sup>d</sup>
Isopentane. ..	72 09	-257	82	0.620 @ 68	93 @ 32	20,808	0	
Toluol ..	92 06	-140	231	0.885 @ 32	86 5 @ 231	18,270	45	102 <sup>d</sup>

<sup>1</sup> Motor Fuel from Farm Products, U.S. Dept. Agr. Misc. Pub. 327, p. 88, 1938.<sup>a</sup> CFR motor method.<sup>b</sup> Properties of secondary reference fuels by Standard Oil Development Co.<sup>c</sup> Estimated.<sup>d</sup> Blending octane numbers at 300°F.Fig. 8-5. Proportionate sources of synthetic liquid fuel if all known fuel reserves in the United States were converted. (Doherty, *Synthetic Liquid Fuels from Coal*.)

The two principal methods of producing oil from coal are the hydrogenation (Bergius) and the gas-synthesis (Fischer-Tropsch) processes.

<sup>1</sup> DOHERTY, J. D., *Synthetic Liquid Fuels from Coal*, Trans. AIME, April, 1949, pp. 116-124.

**Chile.** The use of 10 to 15 per cent alcohol was made compulsory in 1931. A shortage of alcohol forced this down to 6 per cent. Excess sugar cane and absence of native petroleum was the reason for the law.

**Peru.** The government had an income from gasoline imports. As a protection to sugar, alcohol was allowed on farms for their own use.

In other countries (Angola), blends of as high as 75 per cent were sold and used.

### Hydrogenation and Gas Synthesis of Solid Fuels<sup>1</sup>

The three principal sources of synthetic oil are natural gas, oil shale, and coal. Of these, coal is by far the leading potential source of oil in the United States, as is shown in Fig. 8-5.

In general, the gas-synthesis plants are rather inflexible, being approximately 90 per cent gasoline or gasoline plus liquefied petroleum gases; the coal-hydrogenation plant is extremely flexible and can readily produce a high percentage of aviation gasoline, diesel fuel, jet fuel, or fuel oil as desired.

By-products from hydrogenation include industrially valuable tar acids and tar bases, which generally increase with the decreasing rank of the coal. Based on moisture- and ash-free coal, tar acid yields vary from 5 to 15 per cent and tar bases from 2 to 4 per cent. Other portions of the intermediate products could be used for wood preserving and as solvents.

By-products of gas synthesis vary over a wide range from solid wax to methane, the relative quantities depending on the catalyst employed, the ratio of hydrogen to carbon monoxide, and the conditions of temperature and pressure.

#### Processes for Making Motor Fuels from Hydrogenation and Synthesis of Solid Fuels

While it is possible to produce motor fuels from coal, tar, and similar materials by hydrogenation processes, the data thus far available do not indicate that such fuels are likely to be produced as cheaply as by synthesis from gases. These raw materials (coal and derivatives) are, however, the logical sources of replacement fuels for countries having coal deposits in place of oil deposits, particularly where there is a desire to achieve national self-sufficiency regardless of cost.

In the **Bergius process** of coal hydrogenation, pulverized coal is made into a paste by using a carrier oil and recirculated with hydrogen under high temperature and pressure (3,000 to 10,000 psi and 800°F). It is claimed that by this process 65 per cent (by weight) of the coal is recovered as an oil, 25 per cent of the oil being directly suited as a motor fuel. About a ton of additional coal per ton of coal processed is required as fuel, so that actually only about 8 per cent of the coal (17.5 gal of oil per ton) is recovered in liquid form. Production costs of the gasoline are claimed to be about 10 to 13 cents per United States gallon without obsolescence or interest charges. About half of the thermal energy of the original coal is lost. The capital costs of a coal-hydrogenating plant are at present extremely high, but these may be somewhat reduced as development proceeds.

In the **Fischer-Tropsch process** (**Kogasin synthesis**) coal or coke is used as a source of water gas. The mixture of carbon monoxide and hydrogen is purified, additional hydrogen is added, and the combined gas is passed over a catalyst at atmospheric pressure at 200°C. The resulting products differ from other carbon monoxide and hydrogen combinations in that they contain hydrocarbons and no alcohols. They vary in constitution with change of reaction factors and catalyst.

Fischer-Tropsch plants are understood to involve higher operating costs than coal-hydrogenation plants and produce fuels of lower relative octane rating. The catalysts seem to be easily poisoned. Petrol from coal hydrogenation may show an octane rating from 70 to 100 (Cooperative Fuel Research Committee method). However, Fischer-Tropsch plants may be economically operated at smaller size and can also produce by-product oils which can be processed into lubricants, so that in net cost the Fischer products are probably lower than coal-hydrogenation products.

**Low-temperature carbonization** is also often cited as the process that will solve the problem of future motor-fuel supply. In this process, coal is heated to 450 to 700°C instead of to 1000 to 1300°C. The tar yields are from 15 to 35 gal a ton, or two or three times those obtained by high-temperature carbonization. From 1 to 2 gal of light oil can be scrubbed from the gas, and another gallon or two distilled from the tar, the total yield being from 2 to 4 gal. Refining losses would bring the net yield of motor fuel from gas scrubbing and straight distillation of the tar to about the same

Table 8-5. Basic Processes for the Conversion of Coal to Gas<sup>1</sup>

Process . . . . .	Producer gas	Water gas	Lurgi	Bergius	Fischer-Tropsch
Objective . . . . .	A low-Btu industrial gas	Gas for space heating, etc., "city gas"	A high-Btu gas direct from coal without enrichment	Gasoline from coal by hydrogenation	Gasoline from coal by gasification and synthesis
Practical since . . . . .	1839 in Germany	1873 in the U.S.	1936 in Germany	1927 in Germany	1933 in Germany
Basic reactions.	$C + \frac{1}{2}O_2 = CO$	$C + H_2O = CO + H_2$ Glowing coal or coke blasted with steam	$C + H_2O = CO + H_2$ $CO + 3H_2 = CH_4 + H_2O$ $C + 2H_2 = CH_4$	$nC + nH_2 = (CH_2)_n$	$C + H_2O = CO + H_2$ $nCO + 2nH_2 = (CH_2)_n + nH_2O$
Temp. deg F . . . . .	2500	1800	1800	850	650
Pressures . . . . .	Atmospheric	Atmospheric	300 psi	3000-10,000 psi	250 psi
Efficiency, per cent.	72	62	80	30-42	45-50
Estimated relative costs	9¢/Mcf	22¢/Mcf	?	15-18¢/gal	7-8¢/gal
Products . . . . .	CO diluted with air's nitrogen (140 Btu/cu ft)	$CO + H_2$ (300 Btu/cu ft)	$CO$ 23 °C, $H_2$ 49 °C, $CH_4$ 23 °C (500 Btu)	Gasoline, diesel oils, lubricating oils	Gasoline, diesel oil, lubricating oils, alcohol
Remarks . . . . .	In limited industrial use where a lean gas is satisfactory	The great basic conversion reaction, a steppingstone to the future	The linkage between the old water-gas reaction and the modern world of conversion of coal to gases and oils	Once a German triumph; now considered obsolete by most chemical engineers in U.S. oil industry	The conversion process of the present day. Basis on which U.S. engineers are mostly experimenting

<sup>1</sup> SILICOX, L. K., "Patterns of Power," MIT, Mar. 17, 1948, pp. 13, 14.

Table 8-6. Reported Operating Results and Costs from European Gasification Processes<sup>1</sup>

Process	Conventional blue gas		Winkler	Lurgi	Didier	Thyssen-Galocay
	Coal	Coke				
Operating Results						
Gas produced, Mcf/day	25,280	23,000	24,850	28,550	24,800	24,250
Gas produced, cu ft/hr/sq ft	2,820	2,885	13,180	8,430		7,425
Btu/cu ft gas	305	295	263	480	325	330
Coal, lb/Mcf	36 65		33 05		29 55	34 55
Coke, lb/Mcf		35 35		21 88		
Steam, lb/Mcf	59 05	58 20	27.65	42 50	59 05	21 40
Power, kw/hr/Mcf	0 396	1 932 <sup>a</sup>	...	1 478 <sup>a</sup>	0 202	2 065 <sup>a</sup>
Oxygen, cu ft/Mcf			291	131		198
Boiler feed water, gal/Mcf	7 10	6 97	3.32	5 10	7 08	2 56
Cooling water, gal/Mcf	8 38	15.20 <sup>b</sup>	4.79	22.25 <sup>b</sup>	8 52	21 80 <sup>b</sup>
Operating Costs						
Total investment cost <sup>c</sup>						
Without oxygen plant	\$1,884,000	\$1,588,000	\$1,372,000	\$1,247,000	\$2,145,000	\$1,347,000
With oxygen plant			\$1,753,000	\$1,444,000		\$1,601,000
Investment cost/Mcf/day <sup>c</sup>	\$74 60	\$68.00	\$55 20	\$43 70	\$86 40	\$55 50
Without oxygen plant	\$74 60	\$68.00	\$55 20	\$43 70	\$86 40	\$55.50
With oxygen plant			\$70 60	\$50 65		\$66 00
Production costs/Mcf, cents <sup>c</sup>						
Fuel	7 48	13 78	6 75	8 54	6 04	7 07
Water	0 18	0 24	0.09	0 28	0 18	0 23
Electricity	0 32	1 55		1 18	0 16	1 65
Oxygen			3 95	1 77		2 69
Labor, materials, etc	1 23	1 14	0 91	0 72	1.42	0 91
Maintenance @ 3% investment	0 61	0 57	0 45	0 36	0.71	0 46
Fixed charges (12½% investment). . . . .	2 56	2 36	1.89	1 50	2 97	1 90
Total costs/Mcf <sup>c</sup>	12 38	19 64	14 04	14.35	11.48	14 91

<sup>1</sup> "Low Investment Cost Gas Production Processes," Sec. I, pp. 81-82, Project CS-10, Institute of Gas Technology, Chicago.

<sup>a</sup> Probably due to larger number of electric drives.

<sup>b</sup> Probably due to absence of waste-heat boilers.

<sup>c</sup> All costs are relative and not directly related to United States current costs. They are shown for purposes of comparison only. Even so, later research may completely change the comparisons.

as that obtained in high-temperature carbonization. However, this low-temperature tar may be subjected to the same pressure-cracking processes that are used for petroleum and thus yield 20 to 30 per cent motor fuel. A yield of 7 to 12 gal per ton of coal carbonized is therefore possible.

**Lurgi Pressure Gasification.**<sup>1</sup> It was discovered recently that, if gasification is conducted under sufficient pressure, such as 300 psi, part of the gas comes off as methane, with a heating value three times that of standard water gas. Here gasification and partial catalytic enrichment are combined into one operation, and the overall gasification efficiency is considerably improved. The Lurgi pressure gasification process is an example of a plant designed to take advantage of this opportunity. Prepared coal (or possibly char or lignite) is fed through a pressure-tight chamber into a pressure-gasification retort and there gasified with steam and oxygen. The inner vessel, lined with refractory brick, is water-jacketed to protect the thick-wall pressure shell from the white-hot tornado within. Steam produced in the water jacket provides one of the materials for the gasification process. The gas product, a mixture of water gas and methane, is cleaned and readied for use. If a still higher Btu gas is

<sup>1</sup> "Prospects for the Production of a Substitute for Natural Gas," Federal Power Commission Natural Gas Investigation Staff Report, Docket G-580, pp. 37-41, 1947.

desired, this mixture may be further enriched by transforming some of the water gas into hydrocarbons, to give a high-Btu gas already under pipe-line pressure.

**Winkler Process.** The Winkler system also contemplates complete gasification, but at atmospheric pressure. Pulverized coal is continuously fed to the bottom of a retort by a screw or other conveyor, where it is picked up by the high-velocity incoming oxygen-steam stream and held in suspension a short distance above the grate while burning. This method of firing is known as "fluidizing." It is claimed that the process is both flexible and high in output. The end gas is lower in heat value than that developed by the Lurgi process and would require an enriching additive. The capacity reaches 400 lb of coal per sq ft of grate per hr. The Winkler system can use fine waste coal not exceeding 8 per cent maximum moisture; ash content up to 20 per cent; noncaking (the higher the fusion point of the ash, the better the performance of the coal). Approximately 270 cu ft of oxygen is required per 1,000 ft of gas, or 27 per cent (for synthesis gas).

**Thyssen-Galocsy process** appears to have been designed along lines of the original blast furnace, now better known as the slag producer. The principal advantage over other producers is the slag-removal feature, which enables the use of lower fusion coals.

**Parry Process.** At Grand Forks, N.D., the U.S. Bureau of Mines has a pilot plant in which reactive lignite and subbituminous coal are gasified by steam in an annular externally heated metal retort. This process can produce directly a wide range of gases in varying proportions of hydrogen but requires a sized reactive fuel and therefore does not have the wide application of the powdered-coal process.

**Underground Gasification.** The Bureau of Mines is actively engaged in both pilot-plant and field experiments on underground gasification of coal. Field tests are conducted at Gorgas, Ala., in conjunction with the Alabama Power & Light Co. Thus far the gas produced has been of very low Btu content.

### Characteristics of Coal for Synthesis Fuels<sup>1</sup>

**As Affecting Both Synthesis and Hydrogenation.** Some characteristics of coal will have a bearing on their use for either the gas-synthesis or hydrogenation process. These include ash content, moisture content, storage properties, and, especially, uniformity.

Although high-ash coal can be gasified, it is axiomatic that **low-ash is advantageous** in almost any process using coal and that the value of ash reduction increases with the cost of such processing. Therefore, as gasification for either the gas-synthesis or coal-hydrogenation process and primary liquefaction in the latter process are expensive, it appears that coal washing will be justified.

**High surface moisture** can cause handling difficulties with fine coal. In any case the moisture in coal, if not removed by prior drying, requires heat for evaporation in the processing and therefore may, and very likely will, be a disadvantage.

**Uniformity** is one characteristic of coal that will undoubtedly be extremely important for both the gas-synthesis and hydrogenation processes. Gasification of coal with oxygen or steam to produce synthesis gas or hydrogen is likely to be a delicately balanced operation that will require a constant feed of uniform-quality fuel. Coal for liquefaction in the hydrogenation process must also be uniform, as variations in ash or petrographic constituents could affect the catalyst requirements and operating conditions.

**As Affecting Gas Synthesis.** Characteristics of coal that may affect the gas-synthesis process particularly are the sulphur content, ash-softening temperature,

<sup>1</sup> DOWERTY, J. D., "Synthetic Liquid Fuels from Coal," paper presented at joint fuels meeting of AIME-ASME, White Sulphur Springs, November, 1948. Printed in *Trans. AIME*, April, 1949, pp. 116-124.

**Table 8-7. Fuel and Water Requirements for 10,000 Bbl per Day Synthetic-fuel Plant<sup>1</sup>**

	Hydrogenation	Gas synthesis
<b>Bituminous coal (11,900 Btu/lb):</b>		
Tons/calendar day .....	4,300	5,100
Tons/year .....	1,570,000	1,840,000
For 20-year life of plant .....	31,300,000	36,700,000
Daily mine capacity required (260 days/year) .....	6,000	7,100
<b>Subbituminous coal (9,500 Btu/lb):</b>		
Tons/calendar day .....	5,200	6,400
Tons/year .....	1,900,000	2,300,000
For 20-year life of plant .....	38,000,000	46,000,000
Daily mine capacity required (260 days/year) .....	7,300	9,000
<b>Lignite (7,500 Btu/lb):</b>		
Tons/calendar day .....	6,600	8,100
Tons/year .....	2,400,000	2,900,000
For 20-year life of plant .....	48,200,000	58,380,000
Daily mine capacity required (260 days/year) .....	9,200	11,300
<b>Anthracite (13,500 Btu/lb):</b>		
Tons/calendar day .....		4,500
Tons/year .....		1,619,000
For 20-year life of plant .....		32,380,000
Daily mine capacity required (260 days/year) .....		6,300
<b>Water, minimum stream flow available (spray cooling and recirculation):</b>		
Intake, millions of gal/day .....	9.6	12.1
Net consumption, millions of gal/day .....	6.6	8.1
<b>Water, unlimited stream flow available (no recirculation):</b>		
Intake, millions of gal/day .....	167	167
Net consumption, millions of gal/day .....	0.8	1

<sup>1</sup> DOHERTY, J. D., Synthetic Liquid Fuels from Coal, *Trans. AIME*, April, 1949, p. 123.**Table 8-8. Effect of Sulphur Content of Coal on Synthesis-gas-purification Costs<sup>1</sup>**  
(Based on a plant producing 10,000 bbl of oil per day and 26 lb of coal per thousand cu ft of raw synthesis gas)

Per cent of sulphur in coal ... ..	1	3	5
Investment in purification equipment ..	\$3,865,000	\$5,447,000	\$6,688,000
Recoverable sulphur, tons/day ..	38	118	198
Cost of sulphur removal/ton coal ..	\$0.75	\$1.15	\$1.52
Net cost of purification per ton of coal gasified based on the following various sulphur credits (include credit for heat recovery):			
Credit per long ton of sulphur recovered: \$ 5 ...	\$0.71	\$1.03	\$1.32
\$10 ...	0.67	0.91	1.12
\$15 ...	0.62	0.79	0.91
\$20 ...	0.58	0.67	0.71
\$25 ...	0.55	0.55	0.51

<sup>1</sup> DOHERTY, J. D., AIME-ASME Joint Fuels Conference Paper, White Sulphur Springs, November, 1948, from *Trans. AIME*, April, 1949, p. 122.

and coking properties. Rank of coal is not important; any rank from anthracite to lignite can be used.

As the synthesis gas must be virtually free from sulphur compounds, high-sulphur coal will increase the cost of gas purification. Table 8-8 summarizes recent estimates on the cost of gas purification. These figures indicate that, where a liberal credit can be obtained for sulphur recovered, high-sulphur coals may be acceptable. If little or no credit is available from the sale of sulphur, reduced purification costs alone might justify cleaning the coal.



Coal gasification must be carried on at temperatures of at least 1800°F, and it may be desirable to employ considerably higher temperatures to eliminate tar and gum-forming constituents from the gas. With either nonslagging or slagging processes, the ash-fusion temperature is likely to be an important factor. It must be high enough so that the ash will not fuse in the nonslagging process and low enough to fuse completely in the slagging process.

If coal is to be gasified in the fluidized state, as has been proposed, the coking characteristics may be very important. With strongly coking coal, it may be necessary to recirculate large quantities of noncoking material to prevent agglomeration in the fluidized bed. For the production of synthesis gas by the Parry process, a very reactive noncoking fuel is required, such as lignite or subbituminous coal. Use of the conventional water-gas process would require noncoking fuel, such as anthracite or coke.

In a synthesis plant, approximately one-eighth of the total coal is used to produce steam and power. This may be a conventional boiler fuel.

**As Affecting Hydrogenation.** The matter of coal selection, or coal distribution in the case of a single source of coal, is much more complicated for a coal-hydrogenation plant than for a gas-synthesis plant. A commercial plant using the hydrocarbon

	Per Cent
Process for liquefaction . . . . .	53
Gasification coal for hydrogen . . . . .	12
Coal for producer gas . . . . .	9
Coal for steam and power . . . . .	26
Total . . . . .	100

gases formed in the process as a source of hydrogen would have four different uses for coal, divided approximately as tabulated at left.

The process coal for liquefaction is, of course, the critical portion. The other uses may in some instances be advantageous, as the equipment may be selected to utilize cheaper coals, or portions of the coal from a captive mine that are less desirable for liquefaction.

Common banded bright coals ranging in rank from high-volatile bituminous coal to lignite are generally suitable for liquefaction by coal hydrogenation. The higher rank medium- and low-volatile coals are liquefied to a lesser extent and therefore yield less oil per ton of moisture- and ash-free coal. Anthracite yields virtually no liquid hydrocarbons under hydrogenation conditions.

In addition to the rank of the coal, the petrographic constituents must be considered. Anthraxylon or vitrain in high-volatile and low-rank coals is almost completely (95 to 98 per cent) liquefied. Splint coals give comparatively low liquefaction yields (60 to 87 per cent in those tested). Fusain is the least reactive constituent and gives very low yields. Some cannel and boghead coals that are low in fusain and opaque attritus may be suitable.

In general, splint coals should be avoided. Fusain usually can be eliminated to a considerable extent by dedusting or cleaning the coal.

Usually the lower rank coals are more readily and more completely liquefied than the higher rank coals. This tends to offset the disadvantage of high moisture characteristic of the low-rank coals. The yields for various suitable coals in this process are roughly proportional to the heating values of the coal as received. The yields of tar acids are appreciably greater with lower rank coals.

**Mineral matter in coal** for hydrogenation may have other disadvantages in addition to its direct detrimental effect on displacing coal in the processing, as removal of the mineral matter has been found to result in the removal of an equal weight of oil. The composition of the mineral matter in coal for hydrogenation may also be a factor. Some mineral matter may act as a negative catalyst and require chemicals to neutralize the effect. A high calcium content may contribute to the formation of deposits in the converters. Acidity and chlorine content of the coal also affect the quality and

type of chemicals added. Actual tests are usually needed to measure the extent of these influences, which are seldom serious.

**Sulphur content** and **ash-fusion** temperature are of little consequence in the coal-hydrogenation process.

**As Affecting Gasification.** The requirements for gasification coal to produce hydrogen are the same as for the production of synthesis gas, except that the sulphur content is of less importance, as gas purification is optional and, when used, would not be carried to the low concentration of sulphur compounds required for the synthesis process.

**Table 8-9. Liquefaction Yields of Ranks and Types of Coal and of Their Petrographic Constituents<sup>1</sup>**

<i>Rank, Type, or Petrographic Constituent</i>	<i>Liquefaction Yield, Per Cent by Weight of Dry, Ash-free Coal, Usual Range</i>
Anthracitic rank.....	Less than 70
Bituminous low-volatile rank .....	70-90
Bituminous medium-volatile rank .....	75-95
Bituminous high-volatile and subbituminous ranks .....	85-96
Lignitic rank.....	90-97
Bright-coal type below medium-volatile rank.....	85-97
Splint and semisplint coal types .....	65-85
Cannel and boghead coal types .....	70-98
Translucent anthraxylon, translucent attritus, spore exines, and algae remains..	95-98
Resins .....	98-100
Opaque attritus .....	40-80
Fusain .....	10-50

<sup>1</sup> FIELDNER, DR. ARNO C., HENRY H. STORCH, and LESTER L. HIRST, Bureau of Mines Research on the Hydrogenation and Liquefaction of Coal and Lignite, *U.S. Bur. Mines Tech. Paper* 666, p. 42, 1944.

### Cost of Synthetic Gasoline

While cost estimates are constantly being revised as research progresses, in 1947 the U.S. Bureau of Mines reported that

In contrast to the rising cost of discovering natural crude oil, progress made by the Bureau of Mines and other organizations in synthetic liquid fuels work has indicated production costs considerably lower than previously anticipated. It is estimated that gasoline can be produced from natural gas for  $5\frac{1}{2}$  to 7 cents and from coal or oil shale for  $7\frac{1}{2}$  to  $9\frac{1}{2}$  cents per gallon. These figures are only a few cents higher than the present estimated cost of gasoline from petroleum. At the present rate of progress, synthetic production of petroleum products on a commercial basis is possible within a few years.

However, the Bureau of Mines added, "The replacement by synthetic processes of any large segment of production from natural crude will require many years of conversion and construction."

Doherty estimates costs from gas synthesis at about 12.4 cents per gallon of total products; from hydrogenation as low as 12.6 cents depending upon adjustment of yield. In the hydrogenation field, he estimates that heavy oil could be produced for about 10 cents per gallon or a high percentage of aviation gasoline (89 per cent) and aviation base stock for 15.5 cents. These figures include all costs with annual depreciation of  $6\frac{1}{2}$  per cent but do not include return on the investment such as interest and profit. No credit has been taken for by-products.

Thus far, all such estimates seem to assume a heavy governmental or other subsidy.

### MISCELLANEOUS LIQUID FUELS

#### Alcohol from Wood and Farm Products<sup>1</sup>

Since wood consists of approximately 60 to 80 per cent of carbohydrates (40 per cent alpha cellulose), it provides the most concentrated and satisfactory cellulosic raw

<sup>1</sup> Motor Fuels from Farm Products, *U.S. Dept. Agr. Misc. Pub.*, 327, p. 109, 1938.

material. It is significant that the published reports of the wood-conversion processes indicate a total possible recovery of the various products in excess of 100 per cent of the original raw material for a complete process. Estimates of alcohol recovery vary widely with the process and method of operation but are reported as high as 90 gal per long ton of dry wood. The lignin recovered still finds little commercial use, being largely coked. It will have to have considerable value in order that the process may have any chance of economic success. The fermentable sugars have been used as a source of alcohol or yeast. Softwood is said to yield a higher percentage of fermentable sugars than hardwood, the total sugar, however, produced by any method being approximately the same. The unfermentable sugars are used as a stock feed or as a source of lactic or acetic acids. In summation, wood waste, if available at a nominal cost, might be able to compete with agricultural crops as a source of alcohol and by-products. However, assuming a growth of 1 cord per acre each year, the financial return per acre would be far below that of grain, without considering by-products, which in the case of corn are now of greater value than wood by-products.

**Utilization of Farm Wastes.** Cornstalks, straws, nutshells, and similar cellulosic materials, generally referred to as farm wastes, might be substituted for wood in the manufacture of alcohol by the hydrolyzation processes, as these materials have the same essential constitution as wood. Table 5-18 shows the estimated amounts of cellulosic crop wastes annually produced in the United States and the amount available to industry. The total waste for all crops is estimated to be approximately 260 million tons annually. On this basis, at 30 gal of alcohol per ton, the material would produce 7.8 billion gal of alcohol a year. A profitable use for the by-product lignin, which may equal or exceed the amount of cellulose present, would have a favorable effect on the economic success of these processes.

**Table 8-10. Alcohol Yield from Various Agricultural Products<sup>1</sup>**

Material	Weight, lb/cu ft	Avg yield 99.5 per cent alcohol, gal		Residual solids	
		Per ton	Per acre	Per cent	Lb/ton
Wheat (all varieties) . . . .	48 2	85 0	33 0	26 9	538
Corn. . . . .	45 0	84 0	88 8	22 3	446
Buckwheat . . . . .	38 6	83 3	34 2	25 0	500
Raisins. . . . .	62 5	81 4	101 7	8 3	166
Grain sorghum . . . . .	45 0	79 5	35.5	24 4	488
Barley . . . . .	38 6	79 2	47.9	32 3	646
Rye . . . . .	45 0	78 8	23.8	27.1	542
Molasses, blackstrap . . . .	87 9	70 4	45 0		
Oats . . . . .	25 7	63 6	36 3	42 3	846
Potatoes. . . . .	48 2	22 9	178.0	3 8	76
Sugar beets . . . . .	48 2	22 1	287 0	5.0	100
Sugar cane (Louisiana) . . . .		15 2	268 0		
Grapes . . . . .	38 6	15 1		3 8	76
Apples. . . . .	38 6	14 4	140 0	2 0	40
Pears . . . . .	40 2	11 5	49 3	1 7	34
Carrots . . . . .	40 2	9 8		3 8	76
Sweet potatoes . . . . .	44.2	34 2	141.0	4.6	92
Sugar cane (Hawaii) 18 to 22 months. .			889.0		

<sup>1</sup> Motor Fuels from Farm Products, U.S. Dept. Agr. Misc. Pub. 327, pp. 27, 28, 1938.

#### Waste Sulphite Liquors from Paper-pulp Mills<sup>1</sup>

The liquor obtained as a waste product in the pulping of wood by the sulphite process contains from 2 to 3½ per cent of sugars, about 65 per cent of which is ferment-

<sup>1</sup> Motor Fuels from Farm Products, U.S. Dept. Agr. Misc. Pub. 327, pp. 110-111, 1938.

able to alcohol. Before such a liquor can be fermented, the sulphur dioxide, as well as the acetic and formic acids contained in it, must be neutralized, usually with lime or calcium carbonate. A special type of yeast which has been acclimated to the sulphite liquors is generally used as the fermenting agent. The fermentation requires from 60 to 90 hr and yields a quantity of alcohol equivalent on the average to 1 per cent of the volume fermented. The difficulty is the cost of evaporation, as there are about 2,100 lb of solids in 2,000 gal of waste water per ton of pulp.

The sulphite pulp-cooking method is somewhat analogous to the Scholler dilute-acid wood-conversion process, except that the former effects only minor decomposition of cellulose. It is estimated that the waste liquor from 1,000 kg of cellulose (representing eight to ten times the weight of the cellulose) contains 644 kg of lignin and 311 kg of carbohydrates, together with 425 kg of lignosulphonic acid, calcium salts, proteins, resins, etc. The carbohydrates are mostly sugars and occur somewhat as follows: pentosans, nonfermentable (arabinose), 26.9 per cent; mannose, 15.6 per cent; galactose, 8.1 per cent; glucose, 49.4 per cent. Yields of 15 gal of 95 per cent alcohol per ton of sulphite pulp have been reported. It is also possible to recover sulphur dioxide and residual organic fuel.

The process of utilizing this material has never been employed to any great extent in the United States, although one plant was reported (1938) to be fermenting paper-mill liquor in combination with molasses. If the processing of cellulose farm wastes for paper becomes successful, the waste liquors therefrom might be suitable for alcohol recovery in the same manner as sulphite liquor from wood pulp.

**Sulphite-liquor Alcohol in Sweden.** Sulphite liquor is an important source of industrial alcohol in the Scandinavian countries and in Germany (prewar data). It is estimated that 18 plants in Sweden were using this process as far back as 1930. In 1936, about 25,351,000 liters (6,698,000 U.S. gal) of 100 per cent ethyl alcohol were produced from sulphite liquor in Sweden. About 16,000,000 l (4,227,000 U.S. gal) of this were blended in motor fuels under the name Lattbentyl. Some alcohol is also produced from potatoes in Sweden. There the use of alcohol as a fuel for government-owned motor vehicles has been compulsory since 1934.

#### Light Oils from By-product Coke Ovens<sup>1</sup>

The properties of the important constituents of light oils from by-product coke plants are as shown in Table 8-11.

Crude **by-product light oil** has a specific gravity of 0.85 to 0.88 and weighs 7.0 to 7.3 lb per gal. It has a calorific value of 145,000 Btu per gal, and 3.6 Btu are required to heat 1 gal 1°F.

The **yield of light oils** shows a direct proportionality to the volatile content of the coal, which is approximated by the formula

$$\text{Gal of light oil/ton of coal} = 0.14(V - 8.5)$$

where  $V$  = volatile content of coal

For a given coal, **light oil yield** increases with temperature of carbonization up to 1650°F, beyond which the yield drops. The composition of the light oil also changes, the percentage of benzene increasing with temperature, while the percentage of toluene increases to a maximum of 1475°F and then drops.

Efficiency of recovery, which depends upon many factors of plant construction, condition, and operation, may seriously affect light oil yield, so that any prediction of yield based on coal quality alone must be used with care.

**Benzols** are widely used as solvents for fats, waxes, gums, and resins and hence have many applications in the manufacture of cleansers, paints, insulating varnishes,

<sup>1</sup> Ess, T. J., *The Modern Coke Plant*, *Iron Steel Engr.*, January, 1948, p. C-32.

waterproofing materials, plastics, and synthetic rubber. Pure benzol is the base from which many drugs, insecticides, dyestuffs, and explosives are made.

**Toluol** is used in rubber and paint manufacture and in the manufacture of the explosive TNT. Pure toluol is the base from which saccharin, many dyestuffs, and perfumes are prepared.

**Naphthalene** is used as an antiseptic and insecticide, and it is the base from which many dyestuffs are prepared. It is also used in the manufacture of sulfa drugs and plastics.

**Table 8-11. Properties of Light Oils from By-product Coking<sup>1</sup>**

Constituents...	Benzene	Toluene	Xylene	Naphthalene
Composition crude light oil, per cent . . . . .	56	16	9 <sup>a</sup>	8 <sup>b</sup>
Formula . . . . .	C <sub>6</sub> H <sub>6</sub>	C <sub>7</sub> H <sub>8</sub>	C <sub>8</sub> H <sub>10</sub>	C <sub>10</sub> H <sub>8</sub>
Molecular weight. . . . .	78	92	106	128
Sp gr, 62°F. . . . .	0.868	0.857	0.857	1.15
Boiling point (atmosphere), deg F. . . . .	176	230	282	422
Increase in boiling point, deg F/in. Hg . . . . .	0.61	0.66	0.74	0.83
Lb/cu ft vapor (60°F, 30 in. Hg) . . . . .	0.209	0.244	0.281	0.339
Btu/lb of liquid . . . . .	17,930	18,270	18,410	17,460
Btu/gal of liquid. . . . .	132,100	132,600	133,500	167,300
Btu/cu ft of vapor . . . . .	3,780	4,500	5,210	5,910
Specific heat . . . . .	0.419	0.44	0.383	0.314
Heat of vaporization, Btu/lb. . . . .	167	150	140	

<sup>1</sup> *Iron Steel Eng.*, 1948.

<sup>a</sup> Includes light solvent naphtha.

<sup>b</sup> Includes heavy hydrocarbons. Remaining content of crude light oil includes wash oil (6 per cent) and acid washing loss (5 per cent).

### Coal Tars<sup>1</sup>

Coal tar varies greatly in composition and may be classified according to its method of production as retort-gas tar and oven-gas tar.

**Retort-gas Tar.** This tar is obtained as a condensation product in the hydraulic mains, scrubbers, or condensers in the manufacture of coal gas. It is less fluid and contains less of the lighter hydrocarbons, more naphthalene, anthracene, and their accompanying oils and more free carbon than tars from other sources. In general, the lower the carbonization temperature of any coal, the more fluid the tar and the lower its carbon content. Retort-gas tar contains 20 to 40 per cent of free carbon and yields on distillation from 50 to 75 per cent of pitch, or, if the distillation is carried all the way, 45 to 65 per cent of coke.

**Oven-gas Tar.** This material is obtained in the distillation of coal in by-product ovens. It is similar to retort-gas tar, except that it is more fluid. It contains more of the hydrocarbons and considerably less free carbon, which latter usually runs from 12 to 20 per cent. The composition changes, of course, with the coal, type of oven, and coking temperature.

### By-product Coal Tar<sup>2</sup>

By-product coal tar is a black, rather thick and viscous liquid at ordinary temperatures, with a specific gravity of 1.15 to 1.21. It usually becomes semisolid at about 30°F. Tar is a very complex mixture containing some 300 compounds. In its crude state it is used as a fuel and for road dressing, but by refining it is made to yield many important products.

<sup>1</sup> MANTLE, C. L., "Industrial Carbon," 2d ed. pp. 226-229, D. Van Nostrand Company, Inc., New York, 1946.

<sup>2</sup> Ess, T. J., *loc. cit.*

A typical tar refines somewhat as shown in Tables 8-12 and 8-13.

**Table 8-12. Fractional Products of Coal Tar**

<i>Product</i>	<i>Per Cent</i>
Water.....	1.25
Light oil (221–338°F).....	1.20
Carbolic oil (338–445°F).....	9.48
Creosote oil (445–517°F).....	10.08
Anthracene oil (517–660°F).....	21.71
Pitch (at 660°F).....	56.28
Total.....	100.00

**Table 8-13. Typical Analysis of Tar Distilled to 662°F**

Fixed carbon, per cent.....	84–91
Hydrogen, per cent.....	5–9
Oxygen, per cent.....	2–7
Sulphur, per cent.....	0.3–1.0
Nitrogen, per cent.....	0.6–1.3
Sp gr.....	0.95–1.25
Btu (high).....	17,300–16,000

Each of these fractions may then be further rectified for the production of many products.

Coal tar weighs 9.6 to 10.0 lb per gal and has a calorific value of 155,000 to 165,000 Btu per gal. It requires 4.8 Btu to raise 1 gal 1°F.

**Water-gas Tar.** The tar obtained from carbureted-water-gas manufacture differs mainly from coal tar in the entire absence of tar acids and ammoniacal liquor, and in the small amount of free carbon present, which is usually less than 2 per cent. Water-gas tar on distillation yields from 35 to 60 per cent of pitch, or, if carried further, 20 to 40 per cent of coke of the weight of the dry tar.

**Pintsch, or Oil-gas Tar.** This material comes from the manufacture of oil gas. It is similar to water-gas tar but contains much larger amounts of free carbon, frequently 25 to 30 per cent or even more.

**Uses of Low-temperature Tar.** Coal tar can be burned with equipment suitable for heavy fuel oils if heated to reduce the velocity sufficiently and to aid atomization.

The low-boiling distillates, owing to their “unsaturated” characteristics, form a satisfactory fuel, with a marked degree of antidetonation; the middle or “neutral” oils are suitable for combustion in diesels and are so used in Europe. Starting is likely to be somewhat difficult.

### Pitch<sup>1</sup>

Pitch is the residue obtained in the distillation of coal tar after all the light oils, intermediate fractions, and heavy oils (creosotes, anthracene, etc.) have been distilled.

Pitches may be classified, according to their melting points, into (1) those which are soft at ordinary temperatures and easily melted, (2) those which are midway between soft and hard, and (3) those which are hard and require a much greater amount of heat to convert them to a liquid condition. This division is purely arbitrary. Soft pitches run from melting points of 50 to 70°C, medium from 70 to 90°C, and hard pitches from this point to 140°C or higher. Over a wide range of melting points, the free carbon content and the coking value will increase with the melting point of the pitch. The same holds true for viscosity. Neither of these generalizations applies, however, over small ranges of melting points.

Pitches are made by three methods of distillation:

1. Tar is distilled to a hard “core” pitch of high carbon content and with high melting point (150°C or higher) and then “cut back” with tar distillates to give a pitch with the required melting point.

2. Tar is distilled to the required melting point under vacuum by the use of steam in the still. The steam assists in removing the high-boiling oils and helps to prevent the deposition of coke on the sides of the still.

3. Tar is distilled in direct-fired horizontal stills carrying on the process without steam or vacuum and letting the products of distillation pass off under the pressure at which they were generated.

<sup>1</sup> MANTELL, C. L., *loc. cit.*, pp. 227–229.

Pitch is normally about two-thirds of the weight of the tar from which it was distilled. Its physical character is mainly dependent upon the temperature employed in distillation, but its ultimate chemical analysis is governed by the tars used in its manufacture and the quality and composition of the coals from which the tars were produced.

Pitch is commonly shipped in boxcars. It is in the sizes in which it was removed from the stills and must be given a preliminary crushing in a roll or gyratory crusher.

**Electrolytic Pitch.** This material is the result of the partial distillation of tar, in which only the lighter fractions are driven off. It is semifluid at ordinary temperatures, and its properties are intermediate between those of tar and pitch. It is higher in free carbon and has a higher viscosity than tar. For a number of years, it was used in some localities for making molded carbons but is no longer produced in large quantities.

#### Summer Oil

Summer oil is a crude petroleum oil from which only the lighter fractions have been distilled. It is often admixed with pitches to produce a more plastic mix and lessen its binding power. It is used as a constituent in the mix of extruded carbons as it cuts down the pressure necessary for extrusion.

## CHAPTER 9

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**Table 9-1. Molecular Symbols of Some Hydrocarbons**

Symbol	Hydrocarbon	Symbol	Hydrocarbon	Symbol	Hydrocarbon
CH <sub>4</sub> .....	Methane	C <sub>5</sub> H <sub>12</sub> ...	Pentane	C <sub>9</sub> H <sub>20</sub> ...	Nonane
C <sub>2</sub> H <sub>2</sub> .....	Acetylene	C <sub>6</sub> H <sub>6</sub> .....	Benzene	C <sub>10</sub> H <sub>8</sub> ...	Naphthalene
C <sub>2</sub> H <sub>4</sub> .....	Ethylene <sup>a</sup>	C <sub>7</sub> H <sub>12</sub> ...	Methyl cyclopentane	C <sub>10</sub> H <sub>14</sub> ...	Cymene
C <sub>2</sub> H <sub>6</sub> .....	Ethane	C <sub>8</sub> H <sub>14</sub> ...	Isobutane	C <sub>10</sub> H <sub>16</sub> ...	Turpentine
C <sub>3</sub> H <sub>4</sub> .....	Allylene	C <sub>8</sub> H <sub>16</sub> ...	Hexane	C <sub>10</sub> H <sub>18</sub> ...	Decalin
C <sub>3</sub> H <sub>6</sub> .....	Propylene <sup>a</sup>	C <sub>7</sub> H <sub>8</sub> .....	Toluene	C <sub>10</sub> H <sub>22</sub> ...	Decane
C <sub>3</sub> H <sub>8</sub> .....	Propane <sup>a</sup>	C <sub>7</sub> H <sub>14</sub> ...	Methyl cyclohexane	C <sub>11</sub> H <sub>16</sub> ...	Amyl benzene
C <sub>4</sub> H <sub>6</sub> .....	Butadiene	C <sub>7</sub> H <sub>16</sub> ...	Heptane	C <sub>12</sub> H <sub>10</sub> ...	Diphenyl
C <sub>4</sub> H <sub>8</sub> .....	Butylene	C <sub>8</sub> H <sub>8</sub> .....	Styrene	C <sub>12</sub> H <sub>26</sub> ...	Dodecane
C <sub>4</sub> H <sub>10</sub> ...	Butane <sup>a</sup>	C <sub>8</sub> H <sub>10</sub> ...	Ethyl benzene	C <sub>13</sub> H <sub>12</sub> ...	Diphenyl methane
C <sub>5</sub> H <sub>8</sub> .....	Isoprene	C <sub>8</sub> H <sub>18</sub> ...	Octane	C <sub>14</sub> H <sub>10</sub> ...	Anthracene
C <sub>5</sub> H <sub>10</sub> ...	Pentylene	C <sub>9</sub> H <sub>12</sub> ...	Propyl benzene	C <sub>14</sub> H <sub>14</sub> ...	Butyl benzene
C <sub>5</sub> H <sub>10</sub> ...	Amylene				

<sup>a</sup> Illuminants.

**Table 9-2. Correction Factors for Gas Volume**

The volume, as measured moist at the barometric pressure and known temperature, is multiplied by the appropriate factor shown in the table, to reduce to volume of saturated gas at 30 in. Hg and 60°F

Temp, deg F	Absolute pressure, in. Hg											
	28.4	28.6	28.8	29.0	29.2	29.4	29.6	29.8	30.0	30.2	30.4	30.6
32	1.012	1.019	1.026	1.033	1.040	1.048	1.055	1.062	1.069	1.076	1.084	1.091
34	1.007	1.014	1.021	1.029	1.036	1.043	1.050	1.057	1.064	1.071	1.079	1.086
36	1.003	1.010	1.017	1.024	1.031	1.038	1.045	1.052	1.059	1.067	1.074	1.081
38	0.998	1.005	1.012	1.019	1.026	1.033	1.040	1.047	1.055	1.062	1.069	1.076
40	0.993	1.000	1.007	1.014	1.021	1.028	1.036	1.043	1.050	1.057	1.064	1.071
42	0.989	0.996	1.003	1.010	1.017	1.024	1.031	1.038	1.045	1.052	1.059	1.066
44	0.984	0.991	0.998	1.005	1.012	1.019	1.026	1.033	1.040	1.047	1.054	1.061
46	0.979	0.986	0.993	1.000	1.007	1.014	1.021	1.028	1.035	1.042	1.049	1.056
48	0.974	0.981	0.988	0.995	1.002	1.009	1.016	1.023	1.030	1.037	1.044	1.051
50	0.970	0.977	0.983	0.990	0.997	1.004	1.011	1.018	1.025	1.032	1.039	1.046
52	0.965	0.972	0.979	0.986	0.992	0.999	1.006	1.013	1.020	1.027	1.034	1.041
54	0.960	0.967	0.974	0.981	0.988	0.994	1.001	1.008	1.015	1.022	1.029	1.036
56	0.955	0.962	0.969	0.976	0.983	0.990	0.996	1.003	1.010	1.017	1.024	1.031
58	0.950	0.957	0.964	0.971	0.978	0.985	0.991	0.998	1.005	1.012	1.019	1.025
60	0.946	0.953	0.959	0.966	0.973	0.980	0.986	0.993	1.000	1.007	1.013	1.020
62	0.941	0.947	0.954	0.961	0.968	0.974	0.981	0.988	0.995	1.002	1.008	1.015
64	0.936	0.942	0.949	0.956	0.963	0.969	0.976	0.983	0.990	0.996	1.003	1.010
66	0.931	0.937	0.944	0.951	0.958	0.964	0.971	0.978	0.984	0.991	0.998	1.004
68	0.926	0.932	0.939	0.946	0.952	0.959	0.966	0.972	0.979	0.986	0.992	0.999
70	0.921	0.927	0.934	0.941	0.947	0.954	0.961	0.967	0.974	0.981	0.987	0.994
72	0.915	0.922	0.929	0.935	0.942	0.949	0.955	0.963	0.968	0.975	0.982	0.988
74	0.910	0.917	0.923	0.930	0.937	0.943	0.950	0.956	0.963	0.970	0.976	0.983
76	0.905	0.911	0.918	0.925	0.931	0.938	0.944	0.951	0.957	0.964	0.971	0.977
78	0.899	0.906	0.913	0.919	0.926	0.932	0.939	0.945	0.952	0.958	0.965	0.972
80	0.894	0.901	0.907	0.914	0.920	0.927	0.933	0.940	0.946	0.953	0.959	0.966
82	0.888	0.895	0.901	0.908	0.914	0.921	0.927	0.934	0.940	0.947	0.953	0.960
84	0.883	0.889	0.896	0.902	0.909	0.915	0.922	0.928	0.935	0.941	0.948	0.954
86	0.877	0.883	0.890	0.896	0.903	0.909	0.916	0.922	0.929	0.935	0.942	0.948
88	0.871	0.878	0.884	0.890	0.897	0.903	0.910	0.916	0.923	0.929	0.936	0.942
90	0.865	0.872	0.878	0.884	0.891	0.897	0.904	0.910	0.917	0.923	0.929	0.936
92	0.859	0.866	0.872	0.878	0.885	0.891	0.898	0.904	0.910	0.917	0.923	0.929
94	0.853	0.859	0.866	0.872	0.878	0.885	0.891	0.898	0.904	0.910	0.917	0.923
96	0.847	0.853	0.859	0.866	0.872	0.878	0.885	0.891	0.897	0.904	0.910	0.916
98	0.840	0.847	0.853	0.859	0.866	0.872	0.878	0.885	0.891	0.897	0.903	0.910
100	0.834	0.840	0.846	0.853	0.859	0.865	0.871	0.878	0.884	0.890	0.897	0.903

Table 9-3. Characteristics of Gaseous Fuels<sup>1</sup>

Fuel	Source	Avg composition <sup>a</sup>	High heat value, Btu/cu ft	Remarks
Blast-furnace gas . . .	By-product of iron making	58 % N <sub>2</sub> ; 27 % CO; 12 % CO <sub>2</sub> ; 2 % H <sub>2</sub> ; some CH <sub>4</sub>	90-100	Good fuel when cleaned. Used mainly at source
Butane . . . . .	Refinery by-product and in casing-head gas	C <sub>4</sub> H <sub>10</sub> (usually has some butylene C <sub>4</sub> H <sub>8</sub> and propane C <sub>3</sub> H <sub>8</sub> )	3,200-3,260	Liquefies under slight pressure. Sold as a liquid
Casing-head gas . . .	First fraction, oil wells	Varies. Mostly propane and butane	1,200-2,000	Used mostly in oil fields
Carbureted water gas	Manufactured from coal oil enriched	35 % H <sub>2</sub> ; 34 % CO; 15 % CH <sub>4</sub> ; 13 % C <sub>2</sub> H <sub>4</sub> ; 2 % N <sub>2</sub> ; 1 % CO <sub>2</sub>	500-600	Good fuel but usually costly. At least part of most city gas
Coke-oven gas . . .	By-product coke ovens	48 % H <sub>2</sub> ; 32 % CH <sub>4</sub> ; 8 % N <sub>2</sub> ; 6 % CO; 3 % C <sub>2</sub> H <sub>4</sub> ; 2 % CO <sub>2</sub> ; 1 % O <sub>2</sub>	500-600	Good fuel when cleaned. Often used at source
Natural gas . . . . .	Gas wells	Varies. Mostly CH <sub>4</sub> , C <sub>2</sub> H <sub>6</sub> , C <sub>3</sub> H <sub>8</sub>	950-2,200	Ideal fuel piped to point of use
Oil gas . . . . .	Manufactured from petroleum	54 % H <sub>2</sub> ; 27 % CH <sub>4</sub> ; 10 % CO; 3 % N <sub>2</sub> ; 3 % CO <sub>2</sub> ; 3 % C <sub>2</sub> H <sub>4</sub>	500-550	Used on West coast, often mixed with coke oven
Producer gas . . . . .	Manufactured from coal, coke, wood	59 % N <sub>2</sub> ; 22 % CO; 11 % H <sub>2</sub> ; 6 % CO <sub>2</sub> ; 2 % CH <sub>4</sub>	135-165	Requires cleaning
Propane . . . . .	By-product of gasoline	C <sub>3</sub> H <sub>8</sub>	2,500	Liquefies under low pressure. Sold as liquid
Refinery gas . . . . .	By-product of petroleum processing	Varies, mostly butane and propane	1,200-2,000	Used mainly at refineries. Some is piped
Sewage gas . . . . .	Sewage-disposal plants	65 % CH <sub>4</sub> ; 30 % CO <sub>2</sub> ; 2 % H <sub>2</sub> ; 3 % N <sub>2</sub> ; traces of O <sub>2</sub> , CO, H <sub>2</sub> S	600-700	Many disposal plants meet all power needs with this fuel

<sup>1</sup> "Hauck Industrial Combustion Data," p. 57, Hauck Mfg. Co., Brooklyn, N.Y., 1944.<sup>a</sup> Analyses shown are intended as a guide only. More accurate and individualized analyses will be found under the respective gas descriptions.

Table 9-4. Comparison of Heat Value of Various Gases and Combustible Mixtures

	Water gas	n-Butane	Oven gas	Natural gas	Producer gas		
					Anthracite	Coke	Bituminous
Air required/cu ft gas (air-gas ratio) . . . . .	4.60	31.1	4.41	10.68	1.12	1.03	1.24
Cu ft combustion products/cu ft of gas . . . . .	5.29	33.6	5.11	11.96	1.90	1.85	2.07
Btu content of gas (1 cu ft):							
Gross (hot) . . . . .	550	3,353	511	1,134	151	137	156
Net (cold) . . . . .	508	3,102	456	1,025	142	132	148
Btu content of quantitative mix 1 cu ft:							
Gross (hot) . . . . .	98	105	94	97	71	68	70
Net (cold) . . . . .	91	97	84	88	68	64	66
Btu content of combustion products 1 cu ft:							
Gross (hot) . . . . .	104	100	100	95	80	78	76
Net (cold) . . . . .	96	92	89	86	75	75	71

Table 9-5. Properties of Commercial Gases (AGA)

Gas	Constituents of gas, per cent by volume								Sp gr	
	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CO	H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	Illuminant		
								C <sub>2</sub> H <sub>4</sub>		C <sub>6</sub> H <sub>6</sub>
Natural gas (Birmingham)	...	.	5.0	...	...	90.0	5.0	...	...	0.60
Natural gas (Pittsburgh)	...	...	0.8	...	...	83.4	15.8	...	...	0.61
Natural gas (southern California)	0.7	...	0.5	...	...	84.0	14.8	.	.	0.64
Natural gas (Los Angeles)	6.5	...	...	...	...	77.5	16.0	.	.	0.70
Natural gas (Kansas City)	0.8	...	8.4	...	...	84.1	6.7	.	.	0.63
Reformed natural gas	1.4	0.2	2.9	9.7	46.6	37.1	.	1.3	(C <sub>2</sub> H <sub>6</sub> 0.8)	0.41
Mixed, natural, and water gas	4.4	2.1	4.7	25.5	35.1	23.1	4.7	0.2	0.2	0.61
Coke-oven gas	2.2	0.8	8.1	6.3	46.5	32.1	.	3.5	0.5	0.44
Coal gas (continuous verticals)	3.0	0.2	4.4	10.9	54.5	24.2	.	1.5	1.3	0.42
Coal gas (inclined retorts)	1.7	0.8	8.1	7.3	49.5	29.2	.	0.4	3.0	0.47
Coal gas (intermittent verticals)	1.7	0.5	8.2	6.9	49.7	29.9	.	3.0	0.1	0.41
Coal gas (horizontal retorts)	2.4	0.75	11.35	7.35	47.95	27.15	..	1.32	1.73	0.47
Mixed coke-oven and carbureted water gas	3.4	0.3	12.0	17.4	36.8	24.9	.	3.7	1.5	0.58
Mixed coal, coke-oven, and carbureted water gas	1.8	1.6	13.6	9.0	42.6	28.0	.	2.4	1.0	0.50
Carbureted water gas	3.0	0.5	2.9	34.0	40.5	10.2	.	6.1	2.8	0.63
Carbureted water gas	4.3	0.7	6.5	32.0	34.0	15.5	.	4.7	2.3	0.67
Carbureted water gas (low gravity)	2.8	1.0	5.1	21.0	47.5	15.0	.	5.2	2.4	0.54
Water gas (coke)	5.4	0.7	8.3	37.0	47.3	1.3	....	....	....	0.57
Water gas (bituminous)	5.5	0.9	27.6	28.2	32.5	4.6	....	0.4	0.3	0.70
Oil gas (Pacific Coast)	4.7	0.3	3.6	12.7	48.6	26.3	..	2.7	1.1	0.47
Producer gas (buckwheat anthracite)	8.0	0.1	50.0	23.2	17.7	1.0	.	...	...	0.86
Producer gas (bituminous)	4.5	0.6	50.9	27.0	14.0	3.0	.	...	...	0.86
Producer gas (0.6 lb steam/lb coke)	6.4	...	52.8	27.1	13.3	0.4	.	...	...	0.88
Blast-furnace gas	11.5	...	60.0	27.5	1.0	...	...	...	...	1.02
Commercial butane	.	.	(C <sub>4</sub> H <sub>10</sub> 93.0)	...	...	(C <sub>2</sub> H <sub>6</sub> 7.0)	...	...	...	1.95
Commercial propane	.	.	(C <sub>3</sub> H <sub>8</sub> 100.0)	...	...	...	...	...	...	1.52

Gas	Cu ft air re- quired for com- bustion of cu ft of gas	Btu/cu ft		Cu ft of products of combustion/cu ft of gas				Ulti- mate per cent CO <sub>2</sub>	Btu net/ cu ft of prod- ucts of comb- ustion
				Water vapor	CO <sub>2</sub>	N <sub>2</sub>	Total		
		gross	net						
Natural gas (Birmingham)	9.41	1,002	904	2.02	1.00	7.48	10.50	11.8	86.0
Natural gas (Pittsburgh)	10.58	1,129	1,021	2.22	1.15	8.37	11.73	12.1	87.0
Natural gas (southern California)	10.47	1,116	1,009	2.20	1.14	8.28	11.62	12.1	87.0
Natural gas (Los Angeles)	10.05	1,073	971	2.10	1.16	7.94	11.20	12.7	86.7
Natural gas (Kansas City)	9.13	974	879	1.95	0.98	7.30	10.23	11.9	86.0
Reformed natural gas	5.22	599	536	1.30	0.53	4.16	5.99	11.3	89.6
Mixed, natural, and water gas	4.43	525	477	1.01	0.64	3.55	5.20	15.3	91.7
Coke-oven gas	4.99	574	514	1.25	0.51	4.02	5.78	11.2	87.0
Coal gas (continuous verticals)	4.53	532	477	1.15	0.49	3.62	5.26	11.9	90.7
Coal gas (inclined retorts)	5.23	599	540	1.23	0.57	4.21	6.01	11.9	89.9
Coal gas (intermittent verticals)	4.64	540	482	1.21	0.45	3.75	5.41	10.7	89.0
Coal gas (horizontal retorts)	4.68	542	486	1.15	0.50	3.81	5.46	11.6	89.0
Mixed coke-oven and carbureted water gas	4.71	545	495	1.04	0.62	3.85	5.51	13.9	90.0
Mixed coal, coke-oven, and carbureted water gas	4.52	528	475	1.11	0.50	3.71	5.32	11.8	89.3
Carbureted water gas	4.60	550	508	0.87	0.76	3.66	5.29	17.2	96.2
Carbureted water gas	4.51	534	493	0.75	0.86	3.63	5.24	17.1	94.2
Carbureted water gas (low gravit.)	4.61	549	501	0.98	0.64	3.70	5.31	14.7	94.3
Water gas (coke)	2.10	287	262	0.53	0.44	1.74	2.71	20.1	96.6
Water gas (bituminous)	2.01	261	239	0.47	0.41	1.86	2.74	18.0	87.2
Oil gas (Pacific Coast)	4.73	551	496	1.15	0.56	3.77	5.48	12.9	90.5
Producer gas (buckwheat anthracit.)	1.06	143	133	0.22	0.32	1.34	1.88	19.4	70.5
Producer gas (bituminous)	1.23	163	153	0.23	0.35	1.48	2.05	18.9	74.6
Producer gas (0.6 lb steam/lb coal)	1.00	135	128	0.17	0.34	1.32	1.82	20.5	70.3
Blast-furnace gas	0.68	92	92	0.02	0.39	1.14	1.54	25.5	59.5
Commercial butane	30.47	3,225	2,977	4.93	3.93	24.07	32.93	14.0	90.5
Commercial propane	23.82	2,572	2,371	4.17	3.00	18.82	25.99	13.7	91.2

NOTE: To convert cubic feet of water vapor to pounds, multiply by 0.0475.

## NATURAL GAS

ANALYSES AND CHARACTERISTICS<sup>1</sup>

The generic term natural gas applied to gases commonly associated with petroliferous geologic formations. As ordinarily found they are combustible, but non-inflammable components such as carbon dioxide, nitrogen, and helium are often present.

Although natural gas is generally high in methane, certain fields have special components. The natural gases from the Appalachian field predominate in paraffin hydrocarbons; the gases from some Kansas, Oklahoma, and Texas wells are high in nitrogen and helium; while some Pacific Coast and Rocky Mountain natural gases are high in CO<sub>2</sub>. Some gases contain hydrogen sulphide, in which case the gas is called "sour" natural gas. There is also the possibility that organic sulphur may be found. The olefin hydrocarbons, carbon monoxide, and hydrogen are not present in American gases.

**Natural Gas Not Constant.** Natural gas from a given well does not remain constant in composition, heating value, or specific gravity over the life of the well. If the gas comes into contact with oil or if the well is adjacent to an oil field, it is quite likely that heating value and specific gravity will rise as rock pressure decreases with the

Table 9-6. Typical Natural Gas Analyses<sup>1</sup>

(Expressed as per cent by volume)

Source	CO <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	Sp gr	Btu/cu ft	
						Gross	Net
Birmingham, Ala. <sup>a</sup>	.	5 0	90 0	5 0	0 60	1,002	904
Pittsburgh, Pa. <sup>a</sup>	.	0 8	83 4	15 8	0 61	1,129	1 021
Los Angeles, Calif. <sup>a,b</sup>	6 5	...	77 5	16 0	0 70	1,073	971
Kansas City, Mo. <sup>a</sup>	0 8	8 4	84.1	6 7	0 63	974	879
Kiefer, Okla. <sup>c</sup>	2 4	1.8	64 1	31 7	0 97	1,272	
Park City, Okla. <sup>c</sup>	0 0	1.8	94 4	3.8	0 74	1,076	
Leavenworth, Kans. <sup>c</sup>	0 8	6 3	88 9	3 4	0 62	964	
Moab, Utah <sup>c</sup>	3 6	5.6	90 8	0 0	0 61	967	
Barron County, Ky. <sup>c</sup>	2 5	1.3	23 6	69 7	1 21	1,548	
Caddo Parish, La. <sup>c</sup>	0 9	1.5	97.6	0 0	0 75	1,039	
Abilene, Tex. <sup>c</sup>	0 0	4 6	74 0	20 6	0 72	1,129	
Quanah, Tex. <sup>c</sup>	0 2	5 8	85 5	9 1	0 74	1,011	
Little Rock, Ark. <sup>d</sup>	1 0	2 3	96 7	0 0	0 57	977	
Los Angeles, Calif. <sup>b,d</sup>	25 0	1 3	59 1	14 5	0 88	843	
Palestine, Ill. <sup>d</sup>	0 5	3.9	95 6	0 0	0 58	966	
Buffalo, N.Y. <sup>d</sup>	0 0	0.4	88.1	11 5	0 61	1,093	
Kansas City, Mo. <sup>d</sup>	0 8	8 4	84 1	6 7	0 63	967	
Charleston, W.Va. <sup>d</sup>	0 0	0 7	76.8	22 5	0 67	1,172	
Dry type <sup>e</sup>	0 2	0.6	99 2	0 0	0 56	1,007	906
Wet type <sup>e</sup>	1 1	...	87 0	4 1/	0 71	1,223	1,109
Sweet type <sup>e</sup>	0 0	2.8	73 1	23 8/	0 68	1,166	1,056
Sour type <sup>e</sup> (H <sub>2</sub> S 6.4)...	...	...	58 7	16 5/	0 92	1,489	1,359
Casing-head type <sup>e</sup> ....	...	...	36 7	14 5/	1 29	2,133	1,959

<sup>1</sup> Sources: "Gaseous Fuels," p. 32, AGA, New York, 1948. "Combustion Engineering," pp. 11-16, Combustion Engineering Co., Inc., New York, 1947.

<sup>a</sup> Average as served to city consumers.

<sup>b</sup> Note difference in analyses from two sources. This could be due either to the different times of analyses or to different companies of origin.

<sup>c</sup> BENDING, E. A., "Combustion," July, 1931.

<sup>d</sup> U.S. Bur. Mines Tech. Paper 158.

<sup>e</sup> LEX, "Geology of Natural Gas," p. 1075.

<sup>f</sup> Also contains appreciable amounts of C<sub>3</sub>H<sub>8</sub>, C<sub>4</sub>H<sub>10</sub>, and C<sub>5</sub>H<sub>12</sub>.

depletion of the well. The gas from one well in Clarion County, Pennsylvania, showed a specific gravity of 0.644 in 1902 when the rock pressure was 900 psi, but by 1918 the rock pressure had declined to 80 psi, and the gravity had risen to 0.76.

**Natural-gas Terms.** The term "dry" as applied to natural gas indicates less than 0.1 gal of gasoline per 1,000 cu ft and "wet" more than 0.1 gal per 1,000 cu ft.

"Sweet" and "sour" are terms applied to indicate absence or presence of hydrogen sulphide ( $H_2S$ ). The natural gas of commerce is usually dry.

**Table 9-7. The Uses of Natural Gas in 1946<sup>1</sup>**

Kind of use	Billion cu ft	Per cent
<b>Industrial:</b>		
Oil- and gas-field operations.	960	23.6
Carbon-black production . . .	478	11.7
Petroleum refining. . .	355	8.7
Electric public utilities . . .	307	7.5
Cement plants. . . . .	58	1.4
Other industrial . . .	1,032	25.3
Total industrial	3,190	78.2
Domestic. . . . .	650	16.0
Commercial . . . . .	237	5.8
Total United States consumption .	4,077	100.0

<sup>1</sup> "Report on the Natural Gas Investigation," p. 35, Conclusions and Recommendations, Federal Power Commission, Docket G-580, April, 1948.

**Table 9-8. Effect of Load Factor on Cost of Gas Transmission<sup>1</sup>**  
(Based upon 500-mile pipe line)

Annual load factor, per cent	16-in. line		24-in. line	
	Cents/Mcf	Per cent increase	Cents/Mcf	Per cent increase
100	10.51	.....	6.97	
90	11.59	10.27	7.47	10.01
80	12.95	23.22	8.32	22.53
70	14.70	39.87	9.41	38.59
60	17.02	61.94	10.87	60.09
50	20.28	92.96	12.90	89.99
40	25.17	139.49	15.85	133.43
30	33.31	216.94	20.90	207.81
20	49.60	371.93	31.02	356.85

<sup>1</sup> "Problems of Long Distance Transportation of Natural Gas," Federal Power Commission Staff Report, Docket G-580, 1947.

**Table 9-9. Effect of Length of Line on Cost of Gas Transmission<sup>1</sup>**  
(Assuming 60 per cent load factor operation)

Length, miles	Average cost, cents/Mcf		Per cent decrease	
	16-in. line	24-in. line	To length	To size
100	3.65	2.37	..	35
500	17.02	10.87	7 <sup>a</sup>	36
1,000	34.43	21.97	6 <sup>a</sup>	36
1,500	52.83	33.88	4 <sup>a</sup>	36

<sup>1</sup> "Problems of Long Distance Transportation of Natural Gas," Federal Power Commission Staff Report, Docket G-580, 1947.

<sup>a</sup> Average of the 16- and 24-in. lines.

**Typical Natural Gases.** There is no one composition which might be termed "typical natural gas." Methane and ethane constitute the bulk of the combustibles and  $CO_2$ , nitrogen, and helium the inerts. Most of the natural gas served by utility companies will have under 10 per cent of total inerts, the exact amount varying with the source. The heating value of natural gas served by a utility company is usually between 1,000 and 1,100 Btu although frequently above the latter figure. Ordinarily, the ethane content does not exceed 16 per cent.

**Heating Value of Natural Gas.** While a rough higher or gross heating value of natural gas can be computed by adding together the heat contributed by volumetric

percentages of the various simple gas components, this method will usually result in a lower value than that obtained by calorimetric determination. This is because the higher homologues or unsaturated hydrocarbons are frequently grouped and reported as a part of the ethane without separate identification.

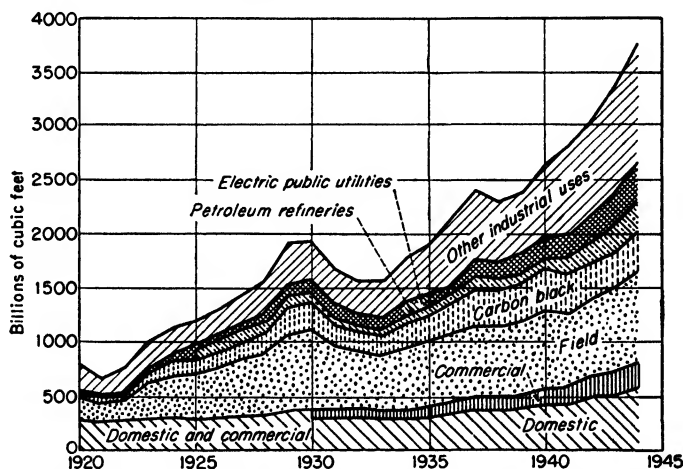


FIG. 9-1. Consumption of natural gas in the United States by uses, 1920 to 1944, in billions of cubic feet (1,000,000,000 cubic feet of gas = 40,000 tons of coal). ("Minerals Yearbook," U.S. Bureau of Mines.)

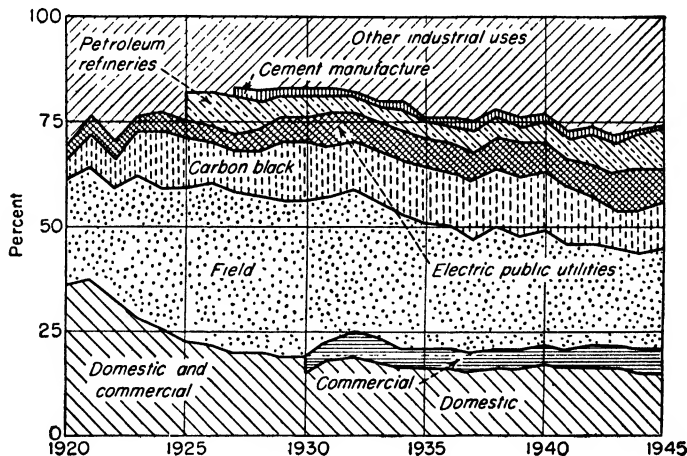


FIG. 9-2. Consumption of natural gas in the United States by uses, 1920 to 1945, in per cent of volume. ("Minerals Yearbook," U.S. Bureau of Mines.)

For the same reason, the corresponding density, under standard conditions of 62°F and 30 in. Hg, will also be lower as calculated. The calculated Btu per pound, however, will be close to its actual value, because of the compensating effect of the lower calculated density.<sup>1</sup>

**Waste of Gas at the Wells.** The prevention of waste has always been a problem of major importance. One-third of all natural gas is produced in association with oil

<sup>1</sup> DE LORENZI, OTTO, "Combustion Engineering," pp. 11-17, Combustion Engineering Co. Inc., New York, 1947.

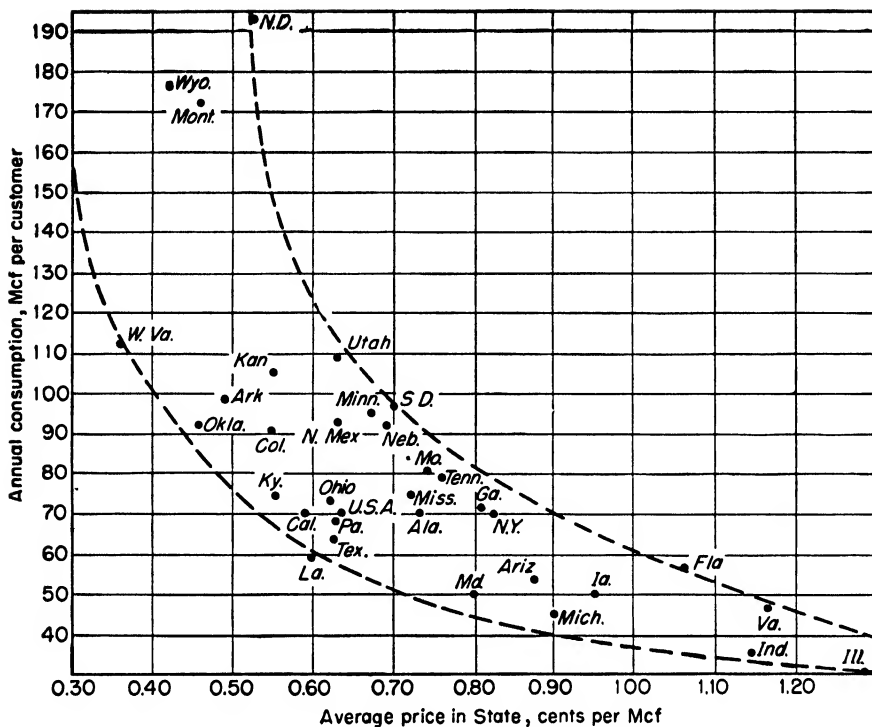


FIG. 9-3. Relation between the residential use of natural gas and the price of gas, by states, 1946. (Federal Power Commission, Docket G580.)

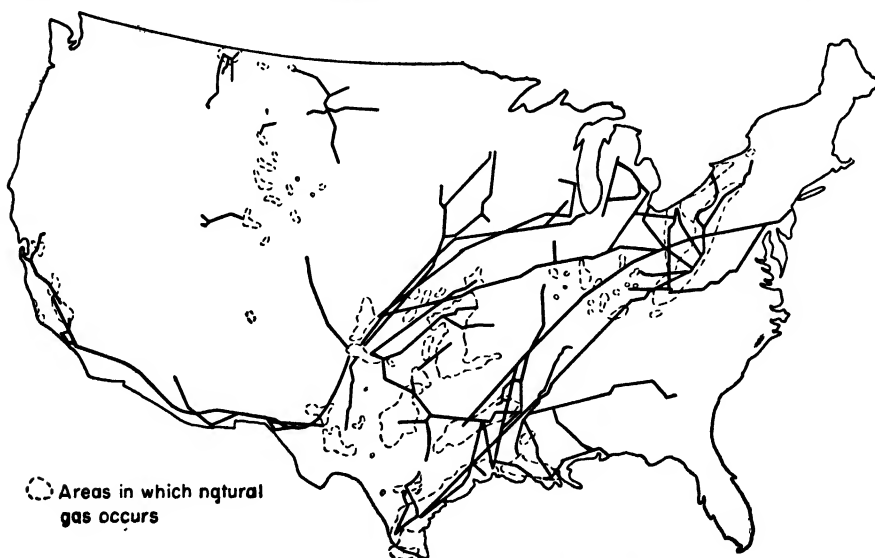


FIG. 9-4. Natural-gas pipe lines in the United States. (Federal Power Commission, Docket G580, Exhibit 433.)

and serves as a principal source of energy in bringing the oil to the surface. Lack of local markets and difficulty of collecting this gas for distance transmission results in a tremendous, though largely undetermined, loss due to "flaring," or blowing from the wells.

It has been estimated that at least 1 billion cu ft of oil-well (casing-head) gas is being wasted daily to the air in Texas alone. On this basis, it appears likely that, in the Southwest area as a whole, the total wastage may exceed 2 billion cu ft a day. This is equal to some 20 per cent of the marketed production of the United States as a whole.

Vigorous methods are now being employed to reduce this loss, including the return of the gas to the underground reservoirs in cycling and pressure-maintenance operations, which should also secure a greater ultimate recovery of oil.

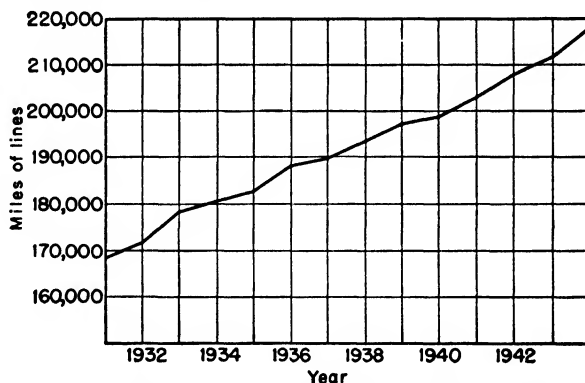


FIG. 9-5. Growth of natural-gas pipe-line mileage in the United States. (*Federal Power Commission, Docket G580.*)

**Consumption of Natural Gas.** Natural gas is used for a wide variety of purposes, indicated broadly by Fig. 9-1, which shows trends in the consumption of natural gas in the United States from 1920 to 1944.

The predominance of industrial uses is notable. In 1944, the most recent year for which complete data are available, consumption of natural gas amounted to 3.7 trillion cu ft, of which about 15 per cent was used for such domestic purposes as cooking, water heating, refrigeration, and house heating. Six per cent went into small commercial uses, including space heating, baking, restaurant cooking, etc. The remaining 79 per cent of the total was used in a host of industrial operations. The most important groups being field uses, the manufacture of carbon black, petroleum refining, refractories, glassmaking, cement production, generation of electricity, and many metallurgical processes.

While industrial users consumed five times as much natural gas as the domestic class, the domestic group contributed 23 per cent more revenue in 1943, as a typical year, than was received from industrial sales.

## MANUFACTURED GAS

### PRESENT METHODS OF GAS MANUFACTURE<sup>1</sup>

Fuel gases obtained by carbonizing coal and gasifying the coke have been in established commercial use both in the United States and abroad for over one hundred years. Commercial processes were also developed for converting oils into gas, in

<sup>1</sup> "Prospects for the Production of a Substitute for Natural Gas," pp. 10-13, Federal Power Commission Staff Report, Docket G-580, Natural Gas Investigations, May, 1947.



order to enrich the gas manufactured from coke and anthracite and to augment its supply. These gases have provided a high-quality fuel for many years in large areas of the country for uses where the price of the fuel is secondary to the convenience of gas service.

There are now in use in the United States at least seven processes for obtaining commercial supplies of manufactured fuel-gas components, five of which yield gas suitable for public-utility purposes.<sup>1</sup> Except for certain noncoking bituminous coals, lignite, and oil shale, these processes make it possible to use almost any of the mineral fuels—coke, coal, oils, and liquefied petroleum gas—as raw materials to manufacture fuel gas.

These methods and raw materials now commercially used to produce manufactured gas in the United States may be summarized briefly as follows:

1. **By-product coke-oven gas** is produced by the high-temperature carbonization of bituminous coal in (a) furnace plants producing metallurgical coke for the iron and steel industry and (b) merchant plants producing coke for subsequent gasification and for many uses as a smokeless solid fuel. This gas, essentially a mixture of methane and hydrogen, has a calorific content of 530 to 540 Btu per cu ft after the removal of the oil, tar, ammonia, and other coproducts. The gross yield is about 11 or 12 thousand cu ft per net ton of coal carbonized. In 1944, one-third of this gas was consumed in the plants and the remaining two-thirds of surplus gas was disposed of outside the plant. Producer gas may, however, be substituted to heat the ovens, in this way releasing more coke-oven gas in accordance with the fluctuating market requirements.

**Table 9-10. Gas Produced and Purchased by Manufactured-gas Utilities in 1948, by Kind of Gas<sup>1</sup>**  
(In millions of cubic feet)

	Gas produced	Gas purchased	Total
Carbureted water gas <sup>a</sup>	310,171	..	310,171
Coke-oven gas . . .	66,557	116,118	182,675
Retort coal gas . . . . .	9,779	.....	9,779
Oil and oil-refinery gas . . .	16,090	5,621	21,711
Total.....	402,597	121,739	524,336

<sup>1</sup> "Gas Facts, 1948," AGA Bureau of Statistics, New York, 1949.

<sup>a</sup> Includes reformed natural, oil refinery, and liquefied petroleum gases; and liquefied petroleum and natural gases used for enriching.

**Table 9-11. Fuels Used by Manufactured-gas Utilities by Type of Use in 1948<sup>1</sup>**  
(Solid fuels in thousands of tons; oil in millions of gallons)

	Oven and retort charge	Bench and producer fuel	Water-gas generator fuel	Boiler fuel	Water-gas enricher	Total
Anthracite . . . . .	53	...	272	265	...	590
Bituminous coal.....	6,452	..	393	491	.....	7,336
Coke.....	7	694	2,485	547	.....	3,733
Oil.....	.....	..	.....	61	1,075	1,308 <sup>a</sup>

<sup>1</sup> "Gas Facts, 1948," AGA Bureau of Statistics, New York, 1949.

<sup>a</sup> Includes 172 million gal used in oil-gas production.

<sup>1</sup> Straight water gas and producer gas have calorific contents too low to distribute economically for public-utility purposes, although they are used as industrial fuel. Blast-furnace gas of still lower calorific content is entirely consumed in plant operations and omitted from the commercial supply.

2. **Blue water gas**, produced by the complete gasification of coal or coke in intermittent or cyclic gas producers is so designated because it is the result of gasifying solid fuel with steam (water) and because the gas burns with a blue flame. With coke or anthracite the gas, which is essentially a mixture of carbon monoxide and hydrogen, has a calorific value of about 290 Btu per cu ft, and the yield is about 50 thousand cu ft per ton of anthracite or coke. With a good grade of bituminous coal, the gas has a calorific value of about 335 Btu per cu ft and the yield is about 42 thousand cu ft per ton of coal.

3. **Carbureted or enriched blue water gas** is produced by admixing, to hot blue water gas described above, oil gas produced by "cracking" gas oil or heavy fuel oil in a highly heated furnace. This enriches the 290-Btu gas to about 530 to 540 Btu per cu ft. About 3.1 gal of oil are used per thousand cu ft of enriched gas, the oil adding between 50 and 60 cu ft of 1,700-Btu gas per gal carbureted.

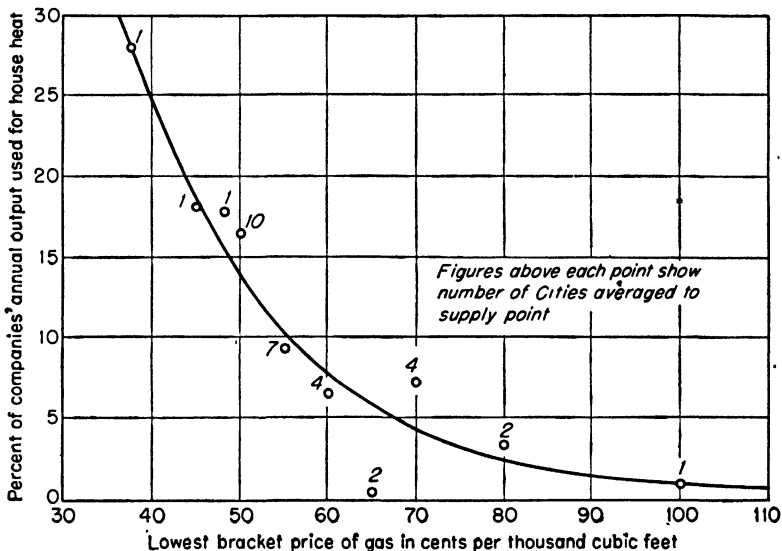


FIG. 9-6. Relation between the use of manufactured gas for house heating and the price of gas.

4. **Oil gas** is produced by the vaporization and thermal cracking of oils with air or steam. One method, known as the Pacific Coast oil-gas process, yields about 1,000 cu ft of 550-Btu gas from 5.5 gal of heavy fuel oil.

5. **Producer gas** is produced by the complete gasification of coke or bituminous coal in a continuous gas producer blown with a mixture of air and steam. This process yields about 120 to 160 thousand cu ft of 130-Btu gas per ton of coke, or about the same volume of 175-Btu gas per ton of coal.

6. **Reformed natural or oil-refinery gas** is produced by thermally cracking a hydrocarbon gas with steam, usually by passing it through the incandescent fuel bed of a blue-gas generator. Depending upon the extent of reforming, the process yields from each 1,000 cu ft of hydrocarbon gas feed about 2,000 cu ft of reformed gas (a mixture of unchanged natural gas, carbon monoxide, and hydrogen) with an approximate calorific value of 540 Btu per cu ft (calculated on the basis of one-third of the methane being converted to carbon monoxide and hydrogen, one part of methane yielding one part carbon monoxide and three parts hydrogen).

7. **Liquefied petroleum gases**, produced from volatile petroleum or natural-gas hydrocarbons (propane and butane), are frequently used as pure gases volatilized from liquid storage, as in the familiar domestic use of "bottled" gas. For commercial or city use, they are more frequently mixed with air, or inert gases, or added as a "cold enrichment" to manufactured gases. For propane, the yield is 0.0365 thousand

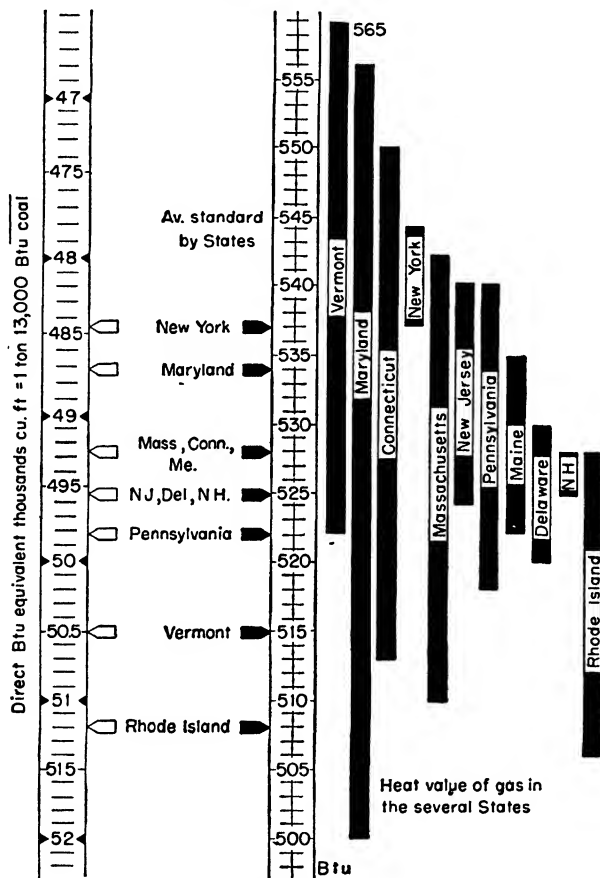


FIG. 9-7. Range of Btu as reported from the various cities in 1944.

cu ft straight propane gas, with a calorific value of 2,521 Btu per cu ft from each gallon of propane. For butane, the yield is 0.0318 thousand cu ft of straight butane gas with a calorific value of 3,267 Btu per cu ft from each gallon of butane.

#### COKE-OVEN GAS<sup>1</sup>

Although produced in an analogous manner to retort coal gases, the size of the charge, the operating temperatures, and other features of the process are different, tending to produce larger amounts of by-products and a more uniform coke. The composition of the finished gas is not very different. Tables 9-12 and 9-13 show typical analyses of by-product coke-oven gas.

<sup>1</sup> SHENIDMAN, Editor, "Gaseous Fuels," p. 43, AGA, New York, 1945. Ess, T. J., The Modern Coke Plant, *Iron Steel Engr.*, January, 1948, p. C-31.

Typical operating results for a coke-oven plant using a high-grade Eastern coal are included in Table 9-14. The coke ovens were fired with producer gas, which had been cooled by passage through a waste-heat boiler.

Additional material on coke-oven operation is also included in the section on by-product coke.

**Yield.** While the primary purpose of most by-product coke ovens is to produce coke for the steel industry and other uses, the gas output from 1 ton of coal may range from 9,300 to 11,500 cu ft with an over-all average of about 10,350. High-rank Appalachian coals give gas yields roughly proportionate to their volatile content, but for coals high in oxygen, the proportionality does not hold. High resin content in the coal increases gas yields. Operation and condition of the ovens may cause even greater variations. For example, for a given coal, gas yield varies directly with coking temperature at a rate of about 1,500 cu ft per ton for each 100°F temperature change. Accordingly, no simple factor can be found to serve as a definite indicator of the gas yield to be expected from a given coal.

**Composition.** Composition of coke-oven gas from a given oven also varies as coking proceeds, being richest at the beginning of the period and gradually thinning out toward the end. This is exemplified by the gas analyses in Table 9-15, taken from the same oven at various times during the coking period. However, since the total gas comes from many ovens at various stages of coking, the actual average gas analysis will normally remain quite uniform.

Coke-oven gas weighs 0.0285 to 0.0305 lb per cu ft. It has a specific heat of 0.0194 to 0.000047 $\ell$  and a specific gravity of 0.34 to 0.040. Its calorific value ranges from 480 to 580 Btu per cu ft before light oil extraction, and 35 to 45 Btu less after debenzolization (values from Ess).

**Calorific Value.** Calorific value of coke-oven gas varies with the volatile content of the coal, as does the specific gravity, but these items are so dependent upon other factors that calculations are impractical.

The total Btu in the gas from 1 lb of coal may run 2,800 to 3,400, increasing with the volatile content of the coal and with the temperature of carbonization. The average seems to be satisfied by the equation

$$\text{Btu in gas/lb of coal} = 2,135 + 29.5V$$

where  $V$  = per cent volatile in the coal

More than 3,400 Btu in the gas from 1 lb of coal indicates excessive degradation of tar vapors by high temperatures.

**Sulphur Compounds.** There are also sulphur compounds in coke-oven gas, making purification essential if the gas is to meet the requirements of metallurgical heating processes and the more stringent requirements of domestic use. These sulphur compounds consist of hydrogen sulphide, carbon disulphide, etc., and will vary from 1 to 6 grains per cu ft (raw gas), depending on the amount and character of the sulphur in the coal.

Sulphur in the gas is usually reported in grains of hydrogen sulphide per 100 cu ft of gas. Results of a series of tests show the gas carrying a range of 100 to 389 grains of  $\text{H}_2\text{S}$  for 1 per cent of sulphur in the coal. General practice, however, indicates that 62 per cent of the sulphur in the coal goes into the coke, the remainder appearing principally in the gas. This relationship may be expressed by the straight-line formula

$$\text{Grains } \text{H}_2\text{S}/100 \text{ cu ft of gas} = 325 (S - 0.15)$$

where  $S$  = per cent sulphur in the coal

Table 9-12. Typical Analyses of By-product Coke-oven Gas

Source.....	a	a	b	c	d
Constituents, per cent by volume:					
Carbon dioxide (CO <sub>2</sub> )	2 0	1.7	1.6	1 8	2 0
Oxygen (O <sub>2</sub> )	0 03		0 5	9 2	0.4
Nitrogen (N <sub>2</sub> )	4 8	0 9	9 0	3 4	5 6
Carbon monoxide (CO)	5 5	5.7	7 8	6 3	7 4
Hydrogen (H <sub>2</sub> )	51 9	56 7	51 5	53 0	54 0
Methane (CH <sub>4</sub> )	32.3	29 6	27 0	31 6	28.0
Ethane (C <sub>2</sub> H <sub>6</sub> )		1 28	1 6		
Hydrogen sulphide (H <sub>2</sub> S)		0 7			
Illuminants	3 2	3 1	1 0		2.6
Sp gr.	0 4				0 38
Btu:					
Gross	569				525
Net	509				467

<sup>a</sup> "Gaseous Fuels," AGA.

<sup>b</sup> GRISWOLD, "Fuels, Combustion, and Furnaces."

<sup>c</sup> "Combustion Engineering," Combustion Engineering Co., New York, 1947.

<sup>d</sup> "The Efficient Use of Fuel," Chemical Publishing Company, Inc., Brooklyn.

Table 9-13. Typical Analyses of By-product Coke-oven Gas<sup>1</sup>

Constituents, per cent by volume:						
Carbon dioxide	1 8	1 4	2 6	3.1	0.1	0 75
Oxygen	0 2	0 5	0 6			
Nitrogen	3 4	4 2	3 7		2 4	12 1
Carbon monoxide	6 3	5 1	6 1	11 9	6 8	6 0
Hydrogen	53 0	57 4	49 7	42 2	27 7	53 0
Methane	31 6	28 5	33 9	37 1	50 0	28 2
Ethane	2 7	2 9	5 2	4 8	13 0	
Benzene (C <sub>6</sub> H <sub>6</sub> )	1 0			0 9		
Density, lb/cu ft	0 0300	0.0265	0 0318	0.0359	0.0393	0 0302
Btu/cu ft:						
Higher	580	526	588	645	807	466
Lower	519	468	527	583	731	414
Btu/lb:						
Higher	19,320	19,820	18,500	17,970	20,550	15,420
Lower	17,310	17,680	16,590	16,250	18,600	13,720
Atmospheric air, <sup>a</sup> lb/10 <sup>6</sup> Btu	678	666	677	687	702	667
CO <sub>2</sub> , per cent <sup>a</sup>	11 0	10 0	11 3	12 7	12 3	9 5

<sup>1</sup> "Combustion Engineering," pp. 25-13, Combustion Engineering-Superheater Corp., New York 1947.

<sup>a</sup> At zero excess air

Table 9-14. Typical Coke-oven Operations<sup>1</sup>

	Yield/ton of coal charged, 14,140 Btu/lb	Yield, per cent by weight of coal	Heating value in products	
			Per cent of coal Btu	Per cent total Btu in fuel used
Coke-oven gas (saturated at 60°F)	11,315 cu ft	19.00	22 96	20 36
Heat value of gas, Btu	548			
Tar (16,000 Btu/lb)	12 0 gal, 120 lb	6 00	6 79	6 00
Ammonia	6 3 lb	0 31	0 22	0 20
Coke (dry)	1,400 lb	70 0	63 2	56 0
Losses (by difference)		4 69	6 83	6 14
Total		100.0	100 0	88 7
Coke used in producers for heating ovens	292 lb			11 3
Net coke	1,108 lb			

NOTE: AGA cautions that the data in this table are presented merely to show what results were obtained under a particular set of conditions and are not intended to be used in comparisons to show relative merits of either ovens or retorts.

<sup>1</sup> "Gaseous Fuels," p. 44, AGA, 1948.

Table 9-15. Variation in Gas Composition as Coking Progresses<sup>1</sup>

Hr coking	CO <sub>2</sub>	C <sub>6</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	O <sub>2</sub>	CO	CH <sub>4</sub>	H <sub>2</sub>	N <sub>2</sub>	Btu/cu ft
2	3.30	1.80	4.00	1.05	0.90	36.65	42.50	10.00	606
4	2.30	1.10	3.10	0.60	2.90	34.50	48.80	6.70	570
6	2.20	1.00	2.80	0.50	3.00	33.60	50.10	6.80	560
8	1.40	0.60	2.50	0.20	3.40	33.65	53.75	3.60	550
10	2.30	0.35	1.75	0.20	2.80	31.20	47.10	14.30	485
12	1.50	0.35	1.85	0.20	4.15	33.40	50.65	7.90	525
15	1.90	0.25	1.80	0.15	3.90	33.20	53.40	5.40	525
19	1.10	....	1.20	0.15	4.70	26.10	55.75	11.00	450

<sup>1</sup> *Iron Steel Engr.*, 1948.WATER GAS<sup>1</sup>

**1. Blue Gas.** Blue gas is produced by the reaction of steam with incandescent carbon. The process is intermittent, consisting of alternate blows or blasting periods, during which the fuel in the generator is heated by blowing air through it, and runs or gasmaking periods during which blue gas is generated by passing steam through the incandescent fuel bed. Operation of modern equipment permits reversal of the flow of gases through the incandescent bed, resulting in "uprun" and "downrun" gas.

The use for pure blue gas, apart from certain applications in forge welding, is for mixing with other commercial gases. It is not commercially made for distribution without mixing, although a few large manufacturers produce it for their own plant use.

Blue gas derives its name from the characteristic color of its flame, which is blue because of the high percentage of hydrogen and carbon monoxide. Because of the use of steam in its manufacture, it is also known as water gas.

Table 9-16 shows typical blue-gas analyses.

Table 9-17 presents operating results for typical water-gas sets.

**2. Carbureted Water Gas.** The manufacture of blue gas (water gas) is the first step in the making of carbureted water gas. It is produced from the former by enriching with oil gas made from gas oil or fuel oil injected (1) into a chamber or chambers heated internally by the combustion of gas formed in the blue-gas generator during the run or (2) onto the fuel bed. It is the most widespread of the manufactured gases because of the flexibility and economics of equipment and process, for meeting the varying demands of the gas load and at the same time providing a low-cost gasification process which uses up its generator fuel completely.

Although illuminants comprise from 8 to 10 per cent of typical carbureted-water-gas samples, they are somewhat different in composition from those of coke-oven gas. Table 9-16 is based on a recent determination of the Bureau of Mines.

The gas composition is influenced by the size and type of coal. (As a guide in water-gas operation with bituminous coal as a generator fuel, the table in the *AGA Proceedings*, Carbureted Water Gas Section, for 1926 by W. J. Murdock is of interest. This shows the analysis of blast, blowrun, blue, and finished gases and the relation of various stages of the cycle to the finished composition.)

**Terzian Factor for Evaluating Oils.** The use of a wide variety of oils for carbureting blue gas requires physical and chemical tests for evaluating the oils. Several such methods are in accepted use, one of which, the Terzian factor, is outlined here as a sample of the general treatment of the evaluation of heavy oils.

In the development and use of the *United Gas Improvement Co. heavy oil process* for carbureted-water-gas manufacture, numerous plant-scale tests have been conducted under varying operating conditions, including varying amounts of blowrun gas, with

<sup>1</sup> SENIDMAN, L., *loc. cit.*, p. 44.

Table 9-16. Typical Analyses of Blue Gas and Carbureted Water Gas<sup>1</sup>

	Blue gas		Carbureted water gas				
	Coke	Bituminous coal	Coke	Anthracite	Bituminous coal		
					Low-gravity backrun	Heavy-oil blowrun	High Btu
Constituents, per cent by volume:							
Carbon dioxide	5.4	5.5	0.9	3.3	3.6	6.0	0.7
Oxygen..	0.7	0.9	.	.	0.4	0.9	0.3
Nitrogen.....	8.3	27.6	6.8	4.2	5.0	12.4	5.8
Carbon monoxide	37.0	28.2	35.0	31.0	21.9	26.8	11.7
Hydrogen..	47.3	32.5	37.4	38.4	49.6	32.2	28.0
Methane...	1.3	4.6	8.1	12.7	10.9	13.5	36.1
Ethane . . .	.	.	1.3	1.05	2.5	.	.
Isobutane (C <sub>4</sub> H <sub>10</sub> )	.	0.7	.	.	6.1	8.2	17.4
Butane (C <sub>4</sub> H <sub>10</sub> )	.	.	0.0	0.0	.	.	.
Butylene (C <sub>4</sub> H <sub>8</sub> )	.	.	0.75	0.45	.	.	.
Propane (C <sub>3</sub> H <sub>8</sub> )	.	.	0.25	0.1	.	.	.
Propylene (C <sub>3</sub> H <sub>6</sub> )	.	.	1.5	0.9	.	.	.
Ethylene (C <sub>2</sub> H <sub>4</sub> )	.	.	6.7	6.9	.	.	.
Liquid hydrocarbons	.	.	1.3	1.05	.	.	.
Sp gr . . . . .	0.57	0.70	. . . .	.	0.54	0.66	0.63
Btu/cu ft:							
Gross . . . . .	287	260	. . .	.	536	530	690
Net.. . . .	262	239	.	.	461	451	621

<sup>1</sup> Compiled from "Gaseous Fuels," AGA, New York, 1948.Table 9-17. Blue-gas (Water-gas) Plant Operation and Gas Analyses<sup>1</sup>

	Coke	Bituminous coal with per cents of blast gas		
		0 per cent	10 per cent	30 per cent
Generator fuel:				
Lb/Mcf. . . . .	40	48	44.5	37.5
Btu/therm . . . .	13.33	14.3	14.1	13.5
Btu/lb.....	13,000	14,000	14,000	14,000
Lb steam:				
Per Mcf. . . . .	40	50	45	35
Per therm . . . .	15	16.7	15	12.6
Gas:				
Btu/cu ft . . . .	300	335	316	277
Sp gr, dry basis . .	0.54	0.55	0.59	0.66
Analysis (per cent):				
Carbon dioxide	5.1	7.0	6.7	6.0
Illuminants.	0.0	1.0	0.9	0.8
Oxygen.....	0.0	0.0	0.0	0.0
Carbon monoxide	40.2	34.4	33.5	31.7
Hydrogen.....	50.0	48.8	44.5	3.58
Methane.....	0.7	4.8	4.6	4.3
Nitrogen.....	4.0	4.0	9.8	21.4
Relative gasmaking capacity of water-gas sets, per cent . . . . .	100	70-90	80-100	100-120

NOTE: The generator fuel and steam consumption per 1,000 cu ft of gas made vary with the condition of the fire, size of fuel used, kind of fuel, coking or noncoking characteristics (bituminous coal), and other variables. Composition of the gas is also affected by these variables.

<sup>1</sup> "Gaseous Fuels," p. 44, AGA, New York, 1948.

or without reforming, and the production of gases varying in heat content from 400 to 700 Btu per cu ft. From a study of these data, it was observed that, for a given grade of generator fuel and heavy oil, there is a definite relation between the heating value of the gas produced, the oil per 1,000 cu ft, the generator fuel per 1,000 cu ft, and the tar produced per 1,000 cu ft and that this relation can be expressed by a constant.

The relation of the Btu, generator fuel per 1,000 cu ft, and oil per 1,000 cu ft, is called the "Terzian factor."

The formula for the "Terzian factor" is

$$\text{Terzian factor} = \frac{K}{A} = \frac{10F + 100C}{A}$$

where  $F$  = generator fuel, lb/thousand cu ft

$C$  = oil used, gal/thousand cu ft

$A$  = Btu/cu ft of make gas

$$K = 10F + 100C$$

The Terzian factor is now used in many plants as an operating-efficiency formula for comparison of daily operating results; the smaller the numerical value of the factor the better the gasification efficiencies.

**Terzian Plant Constant.** The relation of the Btu, generator fuel per 1,000 cu ft, oil per 1,000 cu ft, and tar per 1,000 cu ft is called the "Terzian plant constant."

The formula for the Terzian plant constant is

$$\text{Terzian plant constant} = \frac{K_1}{A} = \frac{10F + 100(C - T)}{A}$$

where  $F$  = generator fuel, lb/thousand cu ft

$C$  = oil used, gal/thousand cu ft

$A$  = Btu/cu ft of make gas

$T$  = tar produced, gal/thousand cu ft

$$K_1 = 10F + 100(C - T)$$

The **Terzian plant constant** can be used to check over-all plant results, including tar production. The plant constant is generally used to compare results of longer periods of operation, since daily figures of tar production are not usually available.

The **Terzian factor** and the **Terzian plant constant** may also be used when using gas oil, refinery oil gas, or natural gas. In the latter two cases, the quantities per thousand cubic feet will have to be expressed as therms and used in the formula the same as the oil per thousand cubic feet.

### Carbureted Water Gas<sup>1</sup>

**Basic Arrangement of Apparatus.** The modern water-gas set consists of (1) a firebrick-lined generator in which a carbonaceous fuel bed is alternately blasted to incandescence by an air jet, and gasified by passing steam through the incandescent carbon with the basic reaction,  $2C + H_2O = 2CO + H_2$ ; (2) a carburetor of similar size, lined with firebrick, with or without checkerbrick, into which oil is sprayed to enrich the "blue gas" from the generator; and (3) a superheater filled with checkerbrick and heated by the blast to "fix" the mixture of gas and carbureted oil.

There are, of course, multitudinous other auxiliaries which, in about the order named, include (1) centrifugal fans for supplying the air blast, (2) boilers for supplying the requisite steam, (3) waste-heat boilers for reclaiming heat from the spent blast

<sup>1</sup> NEWMAN, L. L., C. C. WRIGHT, and A. W. GAUGER, "Test Results on the Use of Anthracite in Heavy-oil Water-gas operation at the Pottsville Gas Works," *Penna. State Coll. Mineral Inds Expt. Sta. Bull.* 32, 1941.



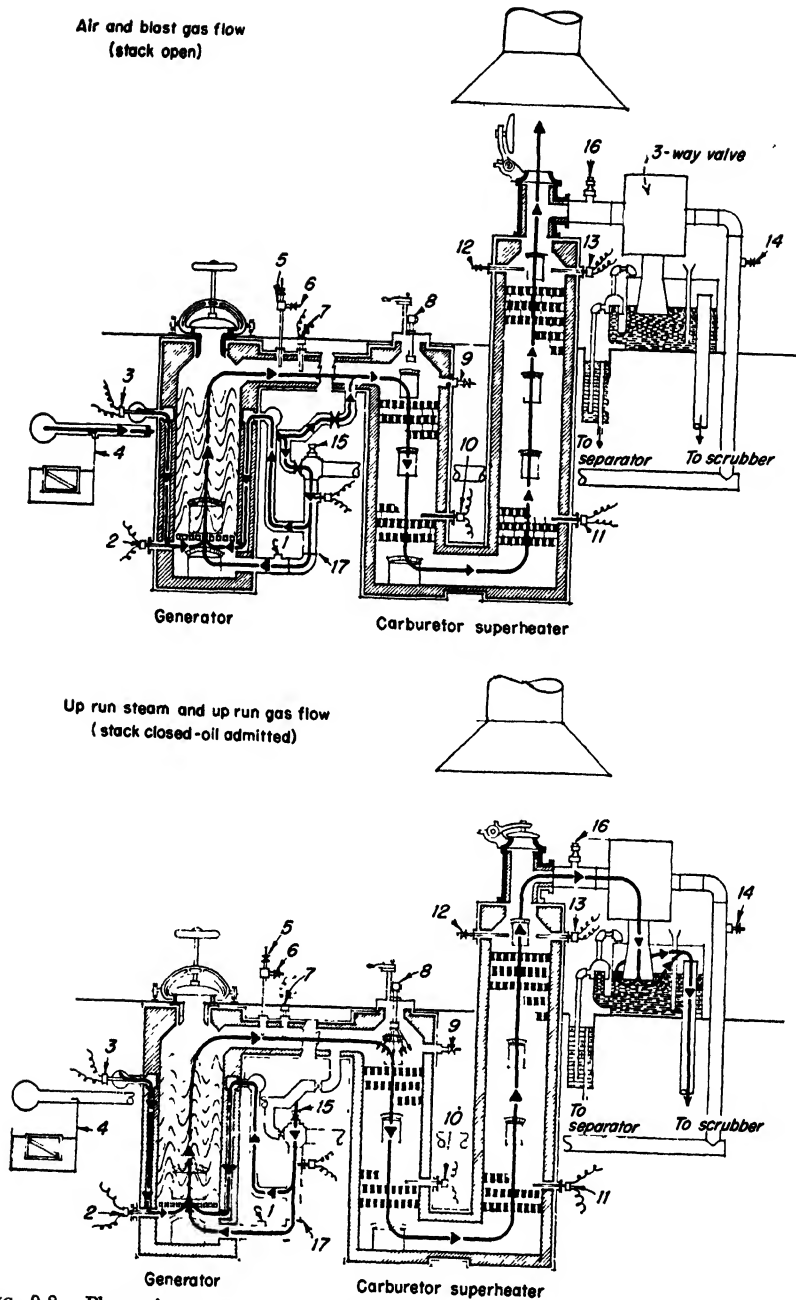


FIG. 9-8. Phases in the operation of water-gas sets. Numbers on cuts refer to location of testing instruments as used by Pennsylvania State College. (*Pennsylvania State College, M.I.E. Bull.* 36.)

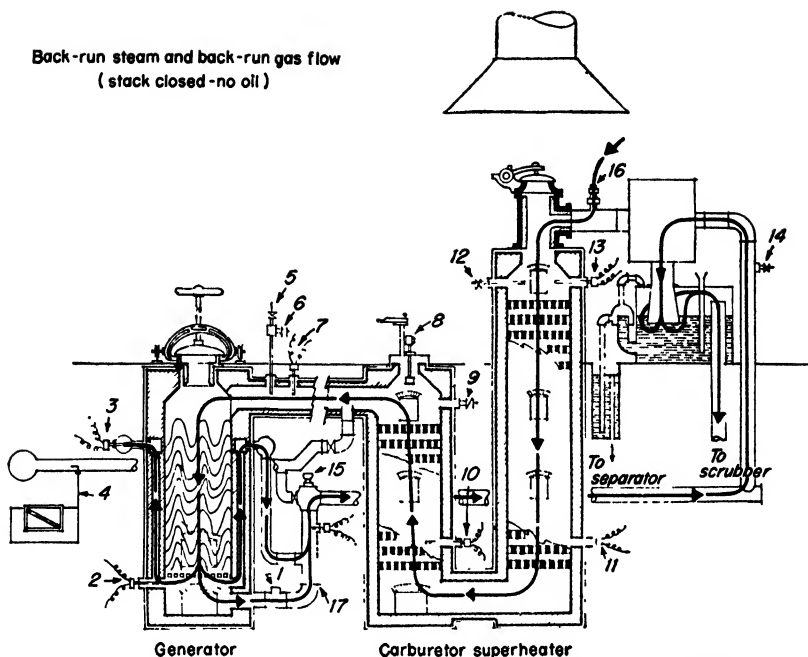


FIG. 9-8 (*continued*). Third phase in the operation of water-gas sets.

gases, (4) wash boxes for removing the tars and other liquid by-products and solid impurities, (5) scrubbers for further cleansing, (6) relief holders for the storage of freshly made unpurified gas, (7) purifiers for removing sulphur compounds, and, finally, (8) storage holders for storing the finished gas until needed in the distributing mains.

**General Conditions of Starting and Operating.** Water-gas operating technique necessarily varies from plant to plant, machine to machine, and fuel to fuel. In the event any changes are made, a reasonable period of time should be allowed for adjustment of cycle, rates of air blast, steam and oil input, and methods of charging and clinker removal.

The capacity of water-gas machines is normally limited by the rate and length of blast. Excessive blast rates will blow abnormal quantities of fine fuel out of the generator; too long a blast may cause an unmanageable clinker. The capacity may be increased somewhat by employing reforming and may be increased appreciably by the judicious use of blowrun combined with reforming.

Conditions vary so much from plant to plant that it would be difficult to label any set of operating conditions or routine as typical without a very complete discussion of gasmaking practices. However, the following is illustrative of the results secured by Pennsylvania State College engineers on a 6-ft machine at Pottsville, Pa.

**Example of Operating Routine and General Results.** After the fire is cleaned, the generator is charged with coal or coke in preparation for the resumption of gasmaking. The first blow period is necessarily long as the entire set has cooled during the shutdown, or clinker-removal period. After shutdown, the first blow may last for 15 to 20 min. After 6 or 7 min of blowing, the carburetor is lighted by inserting a hot rod through the sight cock in the top of the carburetor to ignite the generator blast gas. During this period, the generator blast valve is opened wide, while the carburetor blast valve is adjusted

Table 9-18. Carbureted-water-gas Plant Operation and Gas Analyses (AGA)

Cu ft of blast gas in thousand cu ft of carbureted water gas.....	Normal operation	Operating results with a portion of the blast gas included in the carbureted gas		
	0	300	150	300
Generator fuel, type . . . . .	Coke	Bituminous coal		
Generator fuel:				
Lb/Mcf gas made ..	32	32	35	38 2
Btu/lb . . . . .	12,500	12,500	12,500	12,500
Enricher fuel:				
Type . . . . .	Gas oil	Gas oil	Gas oil	Butane
Gal/Mcf gas made . . . . .	2 95	3 34	2 95	2 8
Btu/gal . . . . .	140,000	140,000	140,000	106,000
Heating values, Btu/cu ft:				
Carbureted water gas . . . . .	540	540	540	540
Water gas in carbureted water gas . . . . .	300	333	333	333
Enricher gas . . . . .	1,600	1,600	1,600	3,240
Blast gas . . . . .	.	140	140	140
Carbureted-water-gas analysis, per cent:				
Carbon dioxide . . . . .	6 0	5.8	6.2	5.3
Illuminants . . . . .	9 8	10.5	9 8	0 6
Oxygen . . . . .	0 0	0 0	0 0	0 1
Carbon monoxide . . . . .	30 0	24 0	26 6	28 9
Hydrogen . . . . .	40 0	25 0	33 3	31 5
Methane . . . . .	10 0	14 4	12 8	3 7
Nitrogen . . . . .	4 2	20 3	11 3	20 8
Butane enricher gas . . . . .				9 1
Sp gr of dry gas . . . . .	0 61	0 73	0 66	0 79

Table 9-19. Typical Operating Data and Costs, Carbureted Water Gas<sup>1</sup>

(All cities shown are in Massachusetts)

City	Make water gas, Mcf/year	Cost coke/ton	Cost oil/gal	Lb generating fuel/Mcf	Gal oil/Mcf	Cost gas/Mcf
1944						
Athol . . . . .	33,767	7 47	0 0768	33 34	2 90	
Cambridge . . . . .	1,851	2 26 <sup>a</sup>				
Boston . . . . .	14,756,416	9 53	0 0490	17 12	3 88	
Fall River . . . . .	1,149,106	9 19	0 0684	29 17	3 04	
Gloucester . . . . .	130,479	8 33	0 0478	24 6	3 37	
Greenfield . . . . .	139,256	10 25	0 0724	32 71	3 05	
Haverhill . . . . .	679,197	12 29	0 0770	28 63	2 62	
Lowell . . . . .	798,534	10 30	0 0489	17 88	3 82	
Brockton . . . . .	953,885	8 10	0 0702	31 31	3 78	
		8 50	0 0699	21.66	3 53	
		10 33	0.0460			
1935						
Athol . . . . .	26,460	8 53	0 0523	27 02	3 01	54 5
Cambridge . . . . .	48,374	6 50	0 0450	38 33	2 51	48 6
Boston . . . . .	476,088	7 17	0 0423	29 50	3 27	
Fall River . . . . .	244,093	7 00	0 0347	29 38	3 04	37 2
Gloucester . . . . .	120,473	8 45	0 0477	37 06	2 65	48 8
Greenfield . . . . .	105,530	10 09	0 0529	27 31	2 75	46 2
Haverhill (low) . . . . .	639,544	8 18	0 0393	15 58	3 80	31 9
Worcester . . . . .	1,500,518	8 92	0 0368	25 67	3 51	36 2
Brockton . . . . .	235,738	7 00	0.0475	26 60	2 95	39 4
Spencer (high) . . . . .	21,232	9 06	0 0492	46 25	3 53	88.6

<sup>1</sup> Commonwealth of Massachusetts, Public Utility Commission Reports, 1935 and 1944.<sup>a</sup> Screenings.

according to the appearance of the blast gases at the stack. If any gas burns near the pilot light at the stack, the carburetor valve is opened gradually until the flame disappears.

When the base of the superheater reaches a temperature of about 1400°F, the first run is put on. No backrun is made during the first run, and the full amount of oil is not admitted. After a predetermined temperature is reached, the normal operating schedule is followed. Again, this varies considerably, but at Pottsville it was about as follows:

Normal operation started at 1560°F, then:

	<i>Min</i>	
Blow . . .	2.59-3.09	} Total runs 3.42 min
Uprun . . .	1.50	
Backrun . . .	1.67	
Final backrun . . .	0.25	
Air purge . . .	0.08	

Approximately 60 per cent of the oil required for enrichment was sprayed into the carburetor and 40 per cent into the generator during the uprun. When oil was reformed, 2 gal were admitted to the generator during the first portion of the backrun in addition to the enrichment oil admitted during the uprun. The enrichment oil varied from 10 to 13 gal per run.

The rate of oil admission is approximately 10 gpm to the carburetor and 5½ gpm to the generator (6-ft machine).

Steam used during the uprun was from 20 to 30 lb per min and during the backrun from 36 to 40 lb, depending on the character of the clinker produced from the coal.

**Table 9-20. Typical Heat Balance of Water-gas Set<sup>1</sup>**

(Heat above 60°F supplied and accounted for per thousand cubic feet average of 5 tests)

Item	Btu	Per cent
Heat input:		
By generator fuel:		
Heat of combustion	379,973	43.01
Sensible heat	38	0.00
By gas oil:		
Heat of combustion	465,938	52.73
Sensible heat	2,536	0.29
By steam, total heat	34,445	3.90
By air:		
Sensible heat in dry air	580	0.07
Sensible heat in moisture	12	0.00
Total heat input .	883,522	100.00
Heat accounted for:		
In gas:		
Heat of combustion	520,000	58.86
Sensible heat of gas	21,000	2.38
In tar:		
Heat of combustion	115,978	13.13
Latent heat	1,036	0.12
Sensible heat	4,400	0.50
In plant drip oil, not available		
In blast products:		
Heat of unburned stack gas	13,993	1.58
Sensible heat blast	51,023	6.12
In undecomposed steam, total heat	17,227	2.05
In water vapor:		
Moist generator fuel . . .	1,342	0.15
Moist blast air . . . . .	560	0.06
Combustion hydrogen . . .	8,410	0.95
In refuse:		
Carbon, generator refuse . . .	29,380	3.33
Carbon, blown-over refuse	957	0.10
Sensible heat . . . . .	1,027	0.12
Radiation, unaccounted, etc . .	97,189	11.00
Total heat accounted for . . . .	883,522	100.00

<sup>1</sup> Summarized from *Penna. State Coll. Mineral Inds. Expt. Sta. Bull.* 32, 1941.

Eleven runs were made between the shutdown period and the first coaling, 10 runs thereafter. After the final charge, as many as 20 runs may be made to burn down the fuel preparatory to the baring down of clinker from the walls.

#### Use of Anthracite in Water-gas Sets<sup>1</sup>

Anthracite has been used in America as a generator fuel in the manufacture of carbureted water gas since 1872. In 1919 a peak was reached of well over a million tons of the generator sizes—grate, broken, and egg. Largely as the result of prolonged strikes in 1922 and 1925–1926, which stimulated material improvements in the use of coke and bituminous coal, rather than for any technical reasons, anthracite was very largely displaced from the market. Today only about 145,000 tons of anthracite are used for this purpose. This is about 13 per cent of the total fuel used by water-gas generators within the normal anthracite-consuming area (11 New England and North Atlantic states). Of the remaining fuel, over 800,000 tons, or 75 per cent of the total, is coke, and 125,000 tons, or 11 per cent of the total, is bituminous coal.

**Advantages of Anthracite.** At one time anthracite was considered a premium fuel for generator purposes. It is the densest and most concentrated form of commercial carbon, allows a greater weight of fuel bed, and permits more heat to be stored after the blow than any other solid fuel.

As a consequence of the high bulk density of anthracite, and the resultant increased heat-storage capacity, the average lowering of the fuel-bed temperature during the "run" or steaming period is small, resulting in high percentages of steam decomposition, and low steam consumption per thousand cubic feet of gas.

**Operating Conditions.** The influence of variables in the ash content and ash-fusion characteristics of various anthracites may be compensated for by adjusting the cycle and steam rates to control the clinker position and condition.

The high bulk density of anthracite requires a long blasting period when bringing a fresh fuel bed up to temperature after removing clinker. It is desirable, therefore, to bring up the depth of the fuel bed gradually by small and frequent charges, thus reducing the duration of the initial blasting period and preventing excessive clinker hardness.

Over the range of blast pressures available at a plant tested by Pennsylvania State College engineers,<sup>2</sup> the effect of wide differences in decrepitation characteristics of anthracites was found to be a negligible factor in ease of operation or operating results. In comparison with the resistance resulting from clinker and from oil carbon deposited in the fuel bed, the resistance resulting from coal decrepitation was of minor significance. Similarly, the quantities of blown-over fuel were found to be a negligible factor in either operation or efficiency.

As has been more than conclusively proved by the continued successful use of anthracite for over 75 years, the quality of the gas made with anthracite is satisfactory, and the specific gravity is such that advantage can be taken of the blowrun for increased capacity wherever economic conditions (price of coal and oil) warrant.

**Selection of Anthracite.** In general, it may be said that the physical differences between anthracites are of greater importance in choosing a generator fuel than the chemical differences.

Physically, reasonable care should be exercised to prevent admission of too high a percentage of fines into the generator. Where fines are excessive, forking or screening the coal is desirable. Other than this, normal size degradation or decrepitation is not likely to be a factor unless the blast pressure used is abnormally high.

Some anthracites with poor resistance to thermal shock may be expected to give unsatisfactory performance. Clinkering coals are usually avoided by gas-plant operators, largely because of the inconvenience and increased cost of their removal.

<sup>1</sup> NEWMAN, WRIGHT, and GAUGER, *loc. cit.*

<sup>2</sup> *Ibid.*

Chemically, in addition to points which have been covered, the formation of both naphthalene and hydrogen sulphides, both undesirable in city gas, are primarily functions of the oils used and considerably less dependent upon the coal.

Table 9-21. Carbureted-water-gas Operating Results with Various Anthracites<sup>1</sup>

Coal field.....	North- ern	Western middle			Eastern middle			South- ern
Coal size....	Broken	Broken	Broken	Egg	Broken	Egg	Stove	Broken
Proximate analysis:								
Fixed carbon, per cent	84.3	87.2	86.9	86.7	88.8	88.7	88.9	86.0
Volatile matter, per cent	5.3	2.5	3.9	4.3	3.8	3.8	3.6	3.6
Ash, per cent	10.4	9.3	9.2	9.0	7.5	7.5	7.5	10.4
Moisture, per cent	2.1	2.2	3.6	2.5	4.3	2.6	3.7	2.1
Heating value/lb Btu	13,160	13,150	12,975	13,210	13,170	13,360	13,220	12,960
Ash-softening temp, deg F	2,680	2,740	2,790	2,750	2,935	2,960	2,950	2,565
Gas oil:								
Gravity, deg API...	41.4	42.5	42.1	41.8	41.7	42.0	42.1	42.7
Lb/gal	6.81	6.77	6.79	6.80	6.80	6.79	6.79	6.76
Heat value/lb, Btu	19,815	19,847	19,785	19,720	19,730	19,780	19,755	19,765
Heat value/gal, Btu...	135,019	134,384	134,261	134,057	134,203	134,306	134,057	133,670
Operating conditions:								
Cycle length, min....	5.81	6.12	6.32	6.18	6.06	6.13	6.42	6.35
Blow, min	2.66	2.93	3.03	3.00	2.87	2.94	3.15	3.02
Carbon blast on, min...	2.62	2.89	2.99	2.96	2.83	2.90	3.11	2.98
Generator air, cfm....	2,280	2,229	2,140	2,162	2,229	2,204	2,059	2,267
Carburetor air, cfm	710	802	742	774	775	732	701	777
Steam, uprun rate, lb/min	34	34	38	38	33	33	33	38
Steam, backrun rate, lb/min	44	43	40	43	44	44	45	43
Oil, total per run, gal.	7.8	8.6	8.4	8.3	8.6	8.6	8.5	8.9
Oil, rate, gpm.....	5.7	5.8	5.9	6.5	6.4	6.5	6.0	5.6
Operating results:								
Gas made per hr, cfm...	36,421	36,946	36,153	36,847	37,985	38,000	35,987	37,592
Generator fuel/Mcf lb.	35.87	35.37	34.66	35.75	33.98	33.30	34.72	36.26
Oil/Mcf gal	2.15	2.20	2.10	2.10	2.15	2.12	2.12	2.17
Steam/Mcf lb	31.86	30.83	32.46	32.67	30.21	29.85	31.19	32.33
Generator "standard" air/Mcf	1,694	1,730	1,605	1,605	1,604	1,622	1,562	1,704
Carburetor "standard" air/Mcf	527	621	556	575	558	539	532	584
Gas made/sq ft grate/hr, cf	2,753	2,793	2,733	2,785	2,871	2,872	2,720	2,842
Tar per Mcf (estimate), gal	0.13	0.23	...	0.08	0.16	0.12	0.11	0.15
Heat of combustion in gas, per cent	65.95	65.84	...	66.48	67.93	68.83	67.53	65.85

<sup>1</sup> Condensed from more complete tables, *Penna. State Coll. Mineral Inds. Expt. Sta. Bull.* 36.

## OIL GASES<sup>1</sup>

Oil gas is a combination of cracked oil vapors and blue gas produced by reactions analogous to those involved in the production of carbureted water gas, except that the oil gases predominate and the blue gas is present in much smaller quantities. By-product carbon, or lampblack, is produced in considerable quantities.

The introduction of natural gas in the larger centers on the Pacific Coast has decreased the use of this type of gas so that little is now made except in the Pacific Northwest. Previously, low-cost oil available on the West Coast was the reason for the economy of the oil-gas process and for the failure to attack its wasteful feature, the formation of lampblack. Most of the lampblack was burned as boiler fuel rather than sold.

Broadly speaking, two types of equipment are used, the "straight-shot" and the

<sup>1</sup> SHNIDMAN, L., *loc. cit.*, p. 42.

Jones process. Results obtained under test conditions in a double-shell generator employing the Jones process are given in Table 9-22 as are the results of a new high-Btu oil-gas process as described by R. J. Chambers.<sup>1</sup> This utilizes a twin-generator setup producing 950 to 1,000 Btu purified gas. The process is achieved by rebuilding the generator and carbureter of a water-gas set into two downheat and downmake oil-gas generators.

Analysis of a typical oil gas is given in Table 9-23, in which it will be seen that this gas has a much lower specific gravity than the analogous carbureted water gases. It is also lower in illuminants and considerably higher in hydrogen and methane.

Table 9-22. Typical Oil-gas Operation<sup>1</sup>

	Jones process		High-Btu process
Heating value, Btu/cu ft	550	540	960
Heat oil, gal/Mcf	0 925	0 900	1 240
Make oil, gal/Mcf	6 380	6 170	9.010
Lampblack, lb/Mcf (estimated)	12 0	12 0	
Tar, lb/Mcf (estimated)	4 0	4 0	1.11
Btu in gas/gal total oil	75,850	76,430	
Gasification efficiency, per cent	51 6	52 0	
Gas analysis, per cent:			
CO <sub>2</sub> .....	4 6	4 8	2 2-3 9
C <sub>2</sub> H <sub>6</sub> . . . . .	1 2	1 1	
C <sub>3</sub> H <sub>8</sub> . . . . .	3 0	2 6	
O <sub>2</sub> . . . . .	0 4	0 3	0 9 3 2
CO . . . . .	10 4	10 2	0 6-1 8
H <sub>2</sub> . . . . .	47 6	49 7	7 5-14 8
CH <sub>4</sub> . . . . .	27 0	25 9	31-41
N <sub>2</sub> . . . . .	5 8	5 4	18 2-22 5
Sp gr . . . . .	0 476	0.461	0 80-0 86
Illuminants . . . . .	. .	. .	17 9-29 0
Air, cu ft/Mcf . . . . .	. .	. .	2138
Steam, lb/Mcf . . . . .	. .	. .	23 9

<sup>1</sup> SHENIDMAN, L., Editor, "Gaseous Fuels," AGA, 1948.

Table 9-23. Analysis of a Typical Oil Gas (Portland)<sup>1</sup>

CO <sub>2</sub> , per cent. . . . .	1 2	C <sub>4</sub> H <sub>10</sub> , per cent . . . . .	3 9
O <sub>2</sub> , per cent . . . . .	0 5	Sp gr . . . . .	0 37
N <sub>2</sub> , per cent . . . . .	2 4	Btu/cu ft:	
CO, per cent . . . . .	7 7	Gross . . . . .	570
H <sub>2</sub> , per cent . . . . .	54 2	Net.... . . . .	510
CH <sub>4</sub> , per cent . . . . .	30.1		

<sup>1</sup> "Gaseous Fuels," AGA 1948.

### Raw Refinery Oil Gas<sup>2</sup>

In the refining of petroleum products, a small fraction of the throughput usually fails to recondense to remain in the form of a raw gas of mixed composition. The bulk of this gas has been used to heat refinery equipment. Only a limited amount of such gases can be used for direct enrichment of water gas or similar lean gas, largely on account of limitations of gas appliances. However, in certain cases where the refinery is located near a large market, this use is sometimes important. It is also used as a source of auxiliary gas supply for industrial plants.

The composition of raw refinery gas is principally saturated and unsaturated hydrocarbons, giving it a heating value of from 1,300 to 2,000 Btu per cu ft, although in well-operated refineries the heating value is generally maintained between 1,400 and 1,700 Btu. These gases are similar in Btu and specific gravity to the gas produced by

<sup>1</sup> CHAMBERS, R. J., *AGA Monthly*, vol. 29, p. 323, 1947.

<sup>2</sup> "Gaseous Fuels," p. 41, AGA, New York, 1948.

cracking gas oil in a carbureted-water-gas set. Table 9-24 shows typical oil-refinery-gas analyses.

Table 9-24. Typical Analyses of Refinery Oil Gases<sup>1</sup>

	Liquid-phase cracking (Cross) <sup>a</sup>	Vapor-phase cracking	Average of four analyses of Hempel Podbielniak
Constituents, per cent by volume:			
Carbon dioxide . . . . .	0 2	0 2	0.5
Oxygen . . . . .	0 2	0 2	0.2
Nitrogen . . . . .	0 6	0 5	2.2 <sup>b</sup>
Carbon monoxide . . . . .	1 2	1 2	1.4
Hydrogen . . . . .	6 1	13 1	1.9
Methane . . . . .	4 4	23 3	34.4
Ethane . . . . .	72.5	21 9	20.1
Illuminants . . . . .	39 6	39 6	44.1
Sp gr . . . . .	1.0	0.89	1.05
Btu/cu ft:			
Gross . . . . .	1,650	1,475	1,688
Net . . . . .	1,524	1,351	

<sup>1</sup> Compiled from "Gaseous Fuels," AGA, New York, 1948.

<sup>a</sup> Dubbs process produces less illuminants (6.7 per cent), and 65 per cent CH<sub>4</sub> and 16 per cent ethane.

<sup>b</sup> By difference and includes H<sub>2</sub>S, CS<sub>2</sub>, etc.

## REFORMED GASES<sup>1</sup>

### Reformed Refinery Oil Gas<sup>1</sup>

The objective of reforming processes, such as that of the U.G.I. Co. of Philadelphia, is to produce a gas suitable for distribution with any or all of the gases commonly distributed. The composition of the reformed gas may be adjusted to render it suitable for mixing with, or replacing, coal gas, coke-oven gas, carbureted water gas, natural gas, or their mixtures. By mixing reformed gas with uncracked (not reformed) refinery gas or with blue, producer, or blast gas, mixtures essentially similar to coal or carbureted water gas can be made.

The flexibility of a water-gas set permits various types of gases to be produced in different parts of the gasmaking cycle, and by suitable mixing in a relief holder any desired finished gas may be made.

Table 9-25 shows sample analyses of 530-Btu reformed gas produced from oil refinery gas and from natural-gas sources. The amounts of generator fuel and the therms of original gas used per thousand cubic feet of finished gas are shown.

### Reformed Natural Gas

The pyrolysis of natural gas on contact with hot checkerbrick results first in decomposition of less stable ethane, forming methane and freeing H<sub>2</sub> and some C. The second stage is the breakdown of methane to C and H<sub>2</sub>.

**References.** Masser<sup>2</sup> reported on the details involved in reforming natural gas on checkerbrick in oil-gas sets using 1,200-Btu natural gas.

The General Oil Gas Corp. reported on the Faber-Dayton process<sup>3</sup> at Olean, N.Y., where 1,340-Btu natural gas was reformed to various finished gases.

The Odell process was in use on a commercial scale,<sup>4</sup> producing reformed gases as indi-

<sup>1</sup> SENIDMAN, L., *loc. cit.*, p. 41.

<sup>2</sup> MASSER, H. L., *Gas-Age-Record*, vol 54, p. 143, Aug. 2, 1924.

<sup>3</sup> RINCLIFFE, R. G., *AGA, Proc.*, 1930, pp. 1482-1487.

<sup>4</sup> BURDICK, R. H., "Natural Gas Reforming at Toledo," AGA Producers Conference, 1931.



cated in Table 9-25. The references cover examples of operation with recovery and with elimination of carbon black.

Cracking natural gas in a water-gas set has been described by J. S. Duesler.<sup>1</sup>

### Reformed Butane Gas

Typical composition of these gases has not been included in the summary Table 9-25 because the processes are not in commercial use at this time, although they have been extensively studied along with the reforming operations on other gaseous hydrocarbons. The references cited give interesting data on chemical reactions, probable composition and yields, as well as the properties of the reformed gases.

**Table 9-25. Typical Analyses of 530-Btu Reformed Gas<sup>1</sup>**

Source . . . . .	From oil-refinery gas			From natural gas	
Constituents, per cent on volume:					
Illuminants	3 5	5 6	5 7	0 6	0 2
Methane.	17 4	13.5	12 3	27 0	28 0
Ethane..	2 3	3.3	3.3	2 9	5 2
Carbon monoxide	17 9	22 1	24 1	15 4	20 5
Hydrogen	53 0	39.6	40 4	47 2	29 6
Carbon dioxide	2 5	3.4	3 6	2 2	3 2
Oxygen..	0 1	0.1	0 2	0 1	0.1
Nitrogen..	3 3	12.4	10 4	4 6	13 2
Btu . .	530	530	530	530	530
Sp gr . .	0 458	0 614	0 624	0 449	0 608
Fuel, lb/Mcf	7 3	12 8	15 7	6 0	14 0
Gas, therms/Mcf	5 09	4 35	4 07	4 95	4 09

<sup>1</sup> SHNIDMAN, L., Editor, "Gaseous Fuels," p. 42, AGA, New York, 1948.

**Table 9-26. Analyses of Reformed Gases<sup>1</sup>**

	From natural gas		From refinery gas
	Straight-shot generator	Water-gas generator	
Constituents, per cent by volume:			
Carbon dioxide	2 1	1.2	2 3
Oxygen	0 3	0 1	0 7
Nitrogen	1 5	3 8	4 9
Carbon monoxide	13 6	22 3	20 8
Hydrogen.....	48.3	49 8	40 8
Methane.....	33 0	21 9	12 3
Isobutane....	1 2	0 83	3 7
Sp gr .....	0 41	0 44	0 51
Btu:			
Gross.....	559	464	530
Net.....	497	424	475

<sup>1</sup> "Gaseous Fuels," AGA, New York, 1948.

### PRODUCER GAS<sup>2</sup>

Producer gas differs from by-product and retort gases in being made by partial combustion of the coal or coke used as generator fuel. Producer gas is high in nitrogen, which is introduced by the air brought in for combustion. The heating value is low; the specific gravity is high, and the per cent of inerts is high. It is odorless and contains about 23 to 27 per cent of carbon monoxide.

<sup>1</sup> DUESLER, J. S., *AGA, Proc.* 1930, pp. 1488-1490.

<sup>2</sup> SHNIDMAN, L., *loc. cit.*, p. 43.

The composition of producer gas is influenced to a great extent not only by the raw materials and operating cycles used, but by the mechanical equipment involved. The high volatile content of bituminous coal requires a different technique than when anthracite or coke is used as a generator fuel. The resultant gases from these fuels are different. Some steam is generally added to producer operation, introducing blue gas in the finished product.

Producer gas may be used as it comes from the generator ("hot producer gas"), or tar and other impurities may be scrubbed out, yielding "cold clean producer gas." Typical analyses are given in Table 9-27.

### Gas Producers

Individually owned gas producers are frequently used for gas generation industrially where municipal or other utility gas is not available or where the price is out of line with that of producer gas.

In the past, several makes of producers have been available, including the Dover-Galusha, the Wood Producer, the Koller (later Semet-Solvay), the Flynn & Dreffin, and the Sharp Bassett. While some of the older producers of all these makes may sometimes be encountered in the field, the market is currently virtually restricted to the Wellman-Galusha<sup>1</sup> for anthracite (usually rice), the Wood Producer<sup>2</sup> for bituminous coal, and the Koppers-Kerpely<sup>3</sup> for coke or anthracite.

**The Wellman-Galusha Producer.** A two-compartment fuel bin forms the top of the machine, the upper section serves as a storage bin, fed by any suitable fuel-handling device. The lower compartment is separated from the upper by a gastight gate through which the fuel is fed as required. Similar gates cover the tops of each of the four steel feed pipes, which connect the lower bin with the upper feed chamber. Fuel from the gastight lower bin flows continuously through these feed pipes to fill the fire chamber, as the grates discharge the ash from below the fire to make room for incoming fresh coal.

The fuel-feed gates are normally open, but at intervals of once or twice a day, they are closed, while the upper gate in the lower compartment is opened to fill the gastight feeding compartment with fuel. An interlocking mechanism prevents the opening of this upper gate unless all lower gates are closed. It also prevents opening any lower gates while the top gate is open. This prevents loss of gas while charging fuel.

**Sizes and Types of Galusha Producers Available.** The Wellman-Galusha producer is made in a wide variety of sizes, ranging from small units suitable for marine propul-

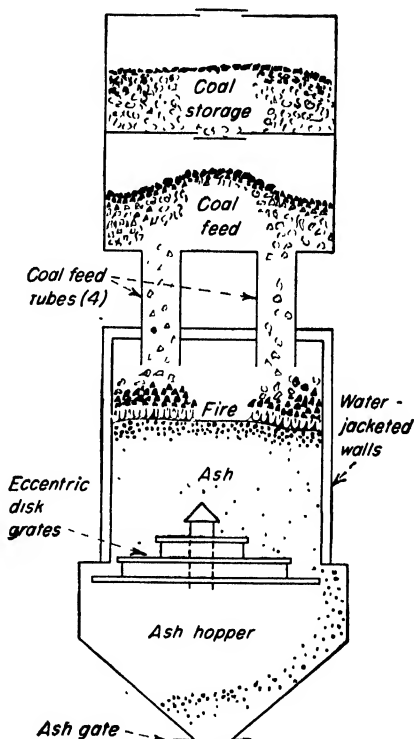


FIG. 9-9. Wellman-Galusha gas producer.

<sup>1</sup> Manufactured by The Wellman Engineering Co., Cleveland, Ohio.

<sup>2</sup> Manufactured by the R. D. Wood Co., Philadelphia, Pa.

<sup>3</sup> Koppers Co., Inc., Engineering and Construction Division, Pittsburgh, Pa.

Table 9-27. Typical Analyses and Properties of Producer Gas from Various Fuels

Fuel . . . . .	Anthracite						Coke	Char- coal	Bitu- minous
	Air				Oxygen				
	Rice	No. 1 buck- wheat	Rice	Barley	Rice	Barley			
	Galusha	Galusha	Galusha	Galusha	Galusha	Galusha			
Blast . . . . .									
Fuel size. . . . .							Air	Oxygen	Air
Producer used . . . . .							Galusha	?	Galusha
Notes.....	a	b		c	d	d e		f	g
Analyses per cent:									
Carbon monoxide.....	22-30	23-2	27-1	21-7	38-9	18-2	31-0	27-1	27-1
Hydrogen.....	5-8	17-7	16-6	18-3	41-4	37-6	9-3	13-3	13-3
Methane.....	1-3	1-0	0-8	0-5	0-87	0-85	0-7	0-4	0-4
Oxygen.....	0-0-25	0-1	0-0	8-2	0-13	0-22	0-05	0-5	0-5
Carbon dioxide . . . . .	1-5-5	8-0	5-0	0-2	17-2	18-2	3-56	4-5	6-4
Nitrogen.....	45-60	50-0	50-4	51-1	1-48	1-85	55-4	52-8	52-8
Btu/cu ft:									
Gross (hot).....	135-160	143	151-1	134-4			137-2	135	135
Net (cold).....	125-158	133	142-2	124-7			132-0	128	128
Approx flame temp, deg F...	3280	3280	3280	..			3150	.	3170
Sp gr, 30°/60°F.....	0.85-0.9	0.86	0.86	0.86			0.9	0.88	0.88
Air-gas ratio. . . . .	1-12	1-12	1-12	0.86			1-03		

<sup>a</sup> General range of values on rice anthracite.

<sup>b</sup> Reported by AGA.

<sup>c</sup> Experimental agitator producer at Canaan, Conn.

<sup>d</sup> Experimental oxygen-blown tests at Trail, British Columbia.

<sup>e</sup> Very brief oxygen-blown tests at Trail, British Columbia.

<sup>f</sup> Normal oxygen-blown operation at Trail, British Columbia.

<sup>g</sup> Small marine Galusha; other tests on industrial size.

sion, laboratory-gas generation, etc., to the popular 10-ft models having a capacity of some 105,000 cu ft of gas per hr. The range of commercial producers is shown as Table 9-28.

As anthracite is free from tar, when this fuel is used it is often possible to dispense with scrubbing towers, baffles, water sprays, and cold gas pumps and to supply hot gas, under pressure, direct to the point of use.

As compared with earlier producers, the present Wellman-Galusha producer possesses such advantages as automatic coal feeding, water-cooled linings to eliminate brickwork, self-generation of steam, and a revolving grate to remove ash automatically.

**Characteristics of Gas.** Inherently, gas generated in such producers from anthracite or coke is a lean fuel; i.e., 1 cu ft of anthracite producer gas carries about 150 Btu, and coke gas about 137 Btu. As a result, existing gas piping may have to be replaced with larger sizes to permit the delivery of a greater volume of gas with the required number of heating units. However, if the gas now used is distributed satisfactorily at such low pressures as 2 or 3 oz, then the present piping may carry sufficient producer gas since it is usually delivered under about 2 lb pressure.

On the other hand, the volume of combustible mixture (air plus gas) is only some 15 to 30 per cent greater with producer gas than with natural or manufactured gas. The air for combustion is less per million Btu than it is for other fuels because the first step in the combustion of the coal, partial burning of carbon to carbon monoxide, has been completed in the producer so that only sufficient air to complete combustion to carbon dioxide is required in the furnace. As practical results, it is usually sufficient to enlarge burner orifices rather than to change burners, and the mixing of air and gas is simplified.

The low Btu content of producer gas leads to frequent misunderstanding concerning its use. It is true that the low Btu content per cubic foot does enter into gas-handling calculations in full proportions; but, as it is the air-gas mixture, and not the gas, that is to be burned in the furnace, items of combustion and furnace design are affected to the much lesser extent of the total volume of mixture required.

**Fuel Requirements.** Anthracite, rice size, is the predominantly popular fuel for Galusha producers. Buckwheat-sized anthracite is also used, particularly on the smaller models. Coke, in the pea or breeze size, is also a satisfactory fuel. Wood waste has proved suitable in some cases, while charcoal is sometimes used on a smaller or marine-type model. Experimental attempts to use the barley size of anthracite on a producer equipped with a mechanical agitator or fuel leveler have not yet placed that size in commercial acceptance.

Coal should be uniformly sized, of square fracture (especially if rice is used), and should be reasonably low in ash content (12 per cent or below). Minimum sulphur content is also of utmost importance when the ultimate gas is to be used in many industrial processes. Volatile content is probably no more critical than on other combustion devices, but a medium content is probably preferable.

**Oxygen Blast and Synthesis Gas.** At the Consolidated Mining & Smelting Co., Trail, B.C., oxygen instead of air is used for the blast in the production of synthesis gas. The Anthracite Institute experimented here with the oxygen blasting of rice

**Table 9-28. Maximum Producer Capacity on Rice Anthracite<sup>a</sup>**

Diameter of producer, ft	Lb coal burned/hr	Cu ft gas/hr (at 70 cu ft/lb)
4	250	
5	400	
6	565	39,500
6½	664	
8	1,000	70,000
10	1,500	105,000

<sup>a</sup> Production on No. 1 buckwheat is approximately 20 per cent greater.

Rice coal burned/sq ft grate. . . 15-21

Dry gas/lb of coal . . . . . 73-79

Probable thermal efficiency:

Gross . . . . . 80-90

Net . . . . . 75-85

and barley anthracite, but, largely because of the small supply of anthracite available for test, the results are not sufficiently conclusive for commercial use.

Synthesis gas produced at Trail ( $\text{CO} + \text{H}_2$  per pound of carbon appearing in the gas) ranged from 40.7 for commercial production on coke to some 44.5 for experimental rice-sized anthracite.

*Uses of Producer Gas.* Typical uses of producer gas as reported by the Wellman Engineering Co. include:

1. All types of heat-treating and annealing in steel mills, both muffle and direct-fired. Its use eliminates most of the scale formation on direct-fired steel products, and it is used both as a fuel and as atmosphere for bright annealing. With auxiliary equipment for removal of  $\text{H}_2\text{S}$  for annealing copper and brass.
2. Firing tunnel kilns for malleable iron, enamel stationary ware, enameling ceramic tiles, firebrick, abrasive grinding wheels, and clay saggers.
3. Firing bakery ovens for bread, cakes, and other food products.
4. Singeing woolen, worsted (finished) cloth.
5. Power generation for small plants and marine use. A special small model is available for the latter purpose.

Producer gas has particular advantages where controlled atmospheres, rich, lean, or variable are needed because of the readiness with which atmospheric oxygen can be excluded. Negligible hydrocarbon content also improves cleanliness and brightness of annealed products.

**Wood Mechanical Gas Producer.**<sup>1</sup> The Wood mechanical gas producer is a self-contained self-supporting machine, fully automatic from the feeding of the coal to the removal of the ash. It is designed for continuous operation on bituminous coal only. It is currently available in only one model, the Type SB-10, 10 ft in diameter inside the brick lining, and capable of gasifying from 400 to 6,000 lb of bituminous coal per hr, depending upon the quality of the coal used (Fig. 9-10).

*Design Features.* Outstanding features of design include positive agitation of the fuel bed by means of a single straight poker bar, which can be replaced; a mechanical coal feeder operated independently of the stirrer-bar drive; a steam seal to prevent gas leakage between the stationary and moving member; a revolving roller-supported ash pan, rotating at the same speed as the producer shell to minimize grinding of the ash and consequent increased resistance to the air blast; an adjustable ash plow, permitting continuous plowing of the ashes regardless of the amount of coal gasified; a stationary agitating blade to move the ash continuously toward the outside of the ash pan; water-cooled top plate; firebrick lining; integral supporting members, driving mechanism, blast, and steam distribution.

*Auxiliary Requirements.* One 5-hp, 1,750-rpm motor is supplied, with average power consumption of about 3 hp. A Wing No. 12-CL-4 centrifugal turboblower is also furnished to supply air to the fire zone. Exhaust steam from the turbine is used to saturate the air blast, augmented as needed by a live-steam supply.

When in continuous operation, the producer will require:

270 gal of water per hr

0.4 lb of steam per lb of coal gasified

50 cu ft of air per lb of coal gasified

*Speeds.* The producer shell, ash pan, and blast hood with the fuel and ash bed will rotate at a speed of one revolution in 10 min. The agitating bar can be rotated at variable speeds. The vertical shaft will rotate at a speed of 1.3 rpm.

*Coal Recommended.* The manufacturer recommends bituminous coal not to exceed 3 in. in size with allowable fines up to 30 per cent.

<sup>1</sup> The R. D. Wood Co., Philadelphia, Pa., manufacturers.

**Operating Results.** In a typical steel-mill test, the following results were secured on a Wood producer:

The coal gasified was Lincoln Gas Coal Co. egg and nut "Pittsburgh vein" of the following analysis:

Moisture, per cent . . . . .	1 38
Volatile, per cent . . . . .	38 40
Fixed carbon, per cent . . . . .	55 90
Sulphur, per cent . . . . .	2 16
Ash, per cent . . . . .	5 70
Btu/lb . . . . .	13,580
Ash fusion, deg F . . . . .	2200

The rate of gasification, depending upon the demand of the heating furnaces, varied from 3,750 to 6,000 lb per hr, or from 47.8 to 76.4 lb of coal per sq ft of fuel-bed area. The gas produced from this coal was of uniform quality and averaged 162.3 Btu (low value at 62°F)

per cu ft containing 46.5 per cent combustibles (Table 9-29).

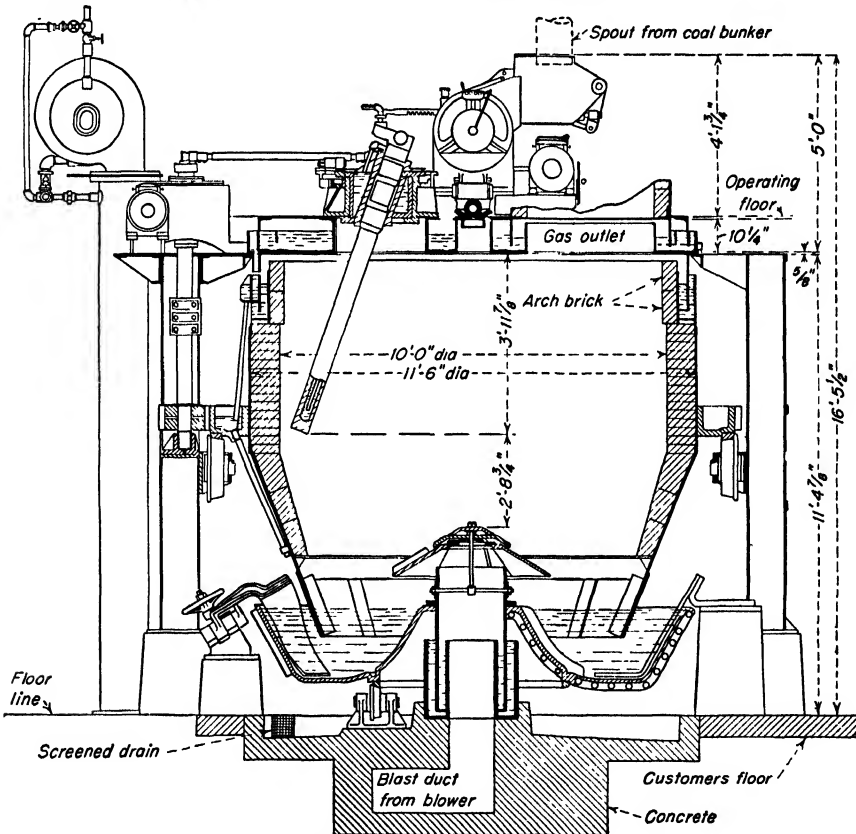


FIG. 9-10. Wood, SB-10 mechanical gas producer.

The analysis of the producer ash, shown in Table 9-30, indicates how thorough the conversion to gas was, the carbon content being only 0.355 per cent of the total carbon charged to the producer.

During several months of operation, there was no hand poking, with the bed remaining level and loose. A gas temperature of 1400°F and a blast temperature of 138°F was maintained. The fire was free from hot spots and blowholes, and the walls free from clinkers.

**Table 9-29. Typical Analysis of Gas from Wood Producer**

	(In per cent)	
	Sample A	Sample B
Carbon monoxide	27.5	26.2
Carbon dioxide	4.5	5.8
Methane	3.8	3.8
Ethylene	0.8	0.8
Hydrogen	15.7	15.7
Oxygen	0.2	0.2
Nitrogen	47.5	47.5

**Table 9-30. Typical Analysis of Ash from Wood Producer**

	Per Cent
Silica..	43.10
Aluminum oxide.	25.95
Ferrie oxide .	23.35
Sulphur	0.44
Phosphorus	0.06
Lime.	1.50
Carbon	5.60

*Principal Applications.* According to the manufacturer, the principal uses are:

Open-hearth-steel melting furnaces	Lehrs for annealing glass
Soaking pits for heating ingots	Rotary kilns for burning limestone
Annealing furnaces	Shaft kilns for burning limestone
Billet-heating furnaces	Brick-burning ovens
Crucible-steel melting furnaces	Glory holes for reheating glass on end of blowpipes

**The Koppers-Kerpely Gas Producer.**<sup>1</sup> To date approximately 124 Koppers-Kerpely gas producers have been built to supply gas for underfiring by-product coke ovens, vertical coke ovens, and ceramic kilns; for the heat-treating of metal; and for mixing with other fuel gases. They have been developed to operate on the smaller sizes of either coke or anthracite.

*Description of Producer.* The Koppers-Kerpely gas producer employs a cylindrical gas generator with a conical eccentric grate and ash-removing device at the bottom and a feed hopper and gas offtake at the top.

The sides of the producer comprise a heavy cast-iron apron which dips into a water seal in the ash pan, a steel water-jacketed section about 8 ft high, and an upper bricklined section to which the bricklined gas offtake is connected. The top is lined with a conical firebrick arch, in the center of which the feed hopper is mounted.

The grate is a built-up cone on a cylindrical section mounted eccentrically on a revolving saucer-shaped cast-iron ash pan. The whole ash assembly turns on a large ball bearing or a grease-lubricated pedestal bearing and carries with it an apron which dips into a water seal around the blast-air-inlet line. A variable speed drive makes it possible to keep the grate moving at all rates of gas production to take full advantage of the eccentric-grate motion to stir the fire and maintain uniform fuel-bed conditions.

On rotation, the eccentricity of the grate and support generates an oscillating motion which crushes the ash between the grate supports and the heavy cast-iron skirt. A plow causes the ash to rise over the sides of the ash-pan saucer, through the water seal, and discharge into the ash-slucing system.

The feed hopper is equipped with a gas tight lid and a double charging bell by means of which the operator may charge the fuel to either the center or the periphery of the fuel bed as required by the condition of the fire.

The water jacket is connected by pipes for circulating the water through a low-pressure steam drum supported above the charging floor. The main function of the water jacket is to prevent formation of side-wall clinkers which would interfere with the removal of ash by the grate and reduce the gasmaking capacity of the producer.

<sup>1</sup> Manufactured by Koppers Co., Inc., Engineering and Construction Division, Pittsburgh, Pa.

*Operation of Producer.*<sup>1</sup> The thickness of the incandescent oxidation zone depends on the size of the fuel used. With small-sized coke breeze it may be only 2 in. thick, while with nut coke it may be 4 in., and with stove coke, 1 ft or more. The restricted oxidation zone formed when gasifying fuel of fine particle size attains a much higher temperature than a thicker oxidation zone resulting from the use of a large-sized fuel. In addition, the ash-fusion temperature of the smaller sizes of fuel is lower than that of the larger sizes. The hotter oxidation zone tends to fuse the ashes and form them

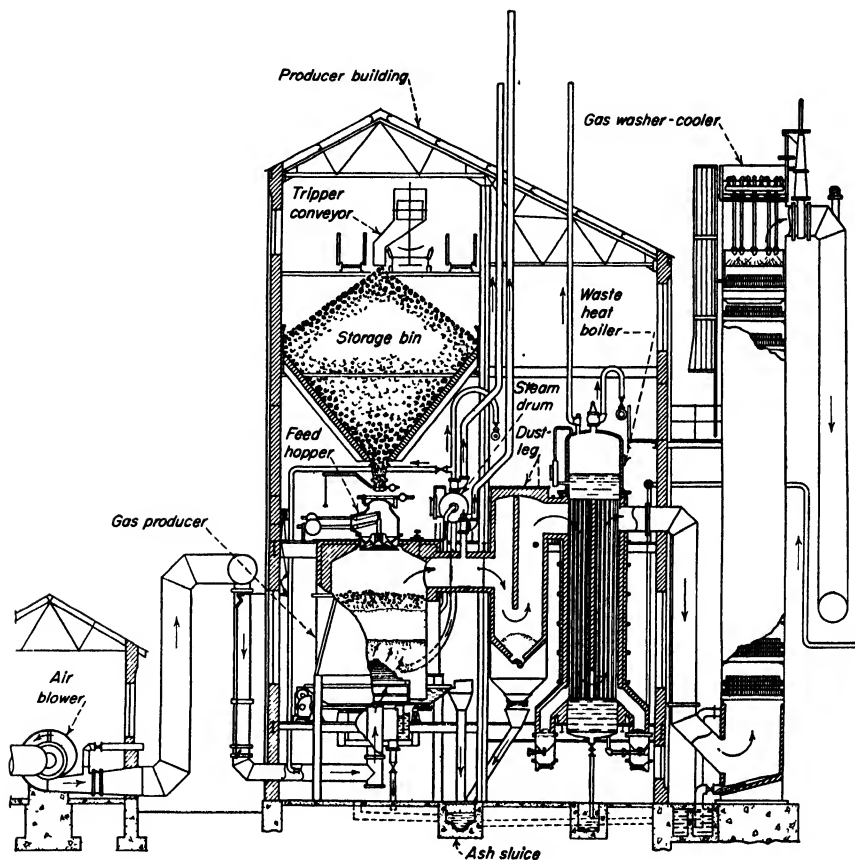


FIG. 9-11. Cross-sectional elevation of a Koppers-Kerpely producer plant.

into large clinkers. This tendency must be opposed in order to keep the fuel bed open and active. Control is maintained through raising the saturation temperature of the air blast, thus increasing the amount of water vapor going through the reaction zones and reducing their temperatures. The gas made will then be higher in carbon dioxide, hydrogen, and gross heating value. However, if forced to comparatively high saturation temperatures to reduce clinker formation, the result may be the production of a gas with a lower net heating value because of the high  $H_2:CO$  ratio. These conditions also bring about a reduction of the capacity of any producer gasifying small-sized fuel.

<sup>1</sup> Table 9-31 and Fig. 9-11 show salient features of design and operation of the Koppers-Kerpely gas producer.



*Typical operating temperatures* are usually in the order of: air blast 130°F; raw gas 1200°F; and gas after the dust leg and waste-heat boiler about 500°F.

*Fuel-gasifying Capacity.* Presuming an adequate supply of properly saturated blast air, the size and nature of the fuel and the fusion point of its ash are the main factors which determine the fuel-gasifying capacity of a gas producer. For a 10-ft Koppers-Kerpely producer, this capacity is 30 to 80 net tons per 24 hr.

**Table 9-31. Operating Data, Koppers-Kerpely Gas Producer<sup>1</sup>**

(10 ft diameter. Gasifying coke at rate of 10 tons per 24 hr)

Coke throughput, net tons/day .. . . .	50
Gas made, Mcf/day .. . . .	7,250
Power for entire plant, kw-hr/day .. . . .	1,000
Water evaporated by jacket boiler, lb/day .. . . .	60,000
Water evaporated by waste-heat boiler, lb/day .. . . .	100,000
Steam for blast saturation, lb/day .. . . .	40,000
Water for gas washing and cooling, thousand gal/day .. . . .	300
Direct labor, man-hr/day <sup>2</sup> .. . . .	24
Typical analyses, per cent:	
Carbon dioxide .. . . .	3.6
Carbon monoxide..... .. .	31.0
Hydrogen .. . . .	9.7
Oxygen .. . . .	0.1
Methane .. . . .	0.2
Nitrogen .. . . .	55.4
Gross heating value of cold gas, Btu/cu ft .. . . .	133
Normal dust after cooling and washing, grains/100 cu ft .. . . .	3-5

<sup>1</sup> Manufacturer's data sheet.

<sup>2</sup> A producer-plant operator, a blower-and-booster engineer, and a fuel charger can operate a plant containing 6 to 8 producers, depending on local conditions.

### LIQUEFIED PETROLEUM GASES<sup>1</sup>

The natural gases which constitute the principal source of liquefied petroleum gas were used as a source of gasoline for many years before the portion which could be kept liquid under pressure was introduced extensively into commerce. Because the natural gases richest in gasoline were drawn from the top of the casings of oil wells, they were called "casing-head" gases, and the gasoline separated both from them and from dry natural gas (unaccompanied by oil) was called "casing-head gasoline." Casing-head gasoline, more recently named and now generally called "natural" gasoline, as distinguished from the gasoline made in refineries, is separated from the gas (1) by compression and cooling or by compression alone; (2) by dissolving under pressure in an oil somewhat less volatile than kerosene, from which it could subsequently be distilled; or (3) by "adsorbing" in a porous material such as "activated" charcoal, from which it is later driven by steam. In every case the higher hydrocarbons, pentane, hexane, etc., which were wanted as gasoline were accompanied by more or less of the lower hydrocarbons, propane, and butane which were not wanted because they made the gasoline too volatile. Originally the natural gasolines were allowed to "weather"; i.e., the dissolved propane and other gases were allowed to escape at ordinary temperature and pressure, accompanied by a large amount of the gasoline vapor, until the gasoline was sufficiently stable for sale. Eventually the process of submitting these escaping gases to "fractional distillation" was introduced, primarily for the purpose of recovering the gasoline they carried with them.<sup>2</sup>

At first fractional distillation of natural gasolines was used only to prevent the loss of gasoline during the removal of propane and butane, which were returned to the natural-gas line. Later, the mixture of propane and butane with some ethane and

<sup>1</sup> Propane, Butane, and Related Fuels, *NBS (U.S.) Letter Circ.* 503, Sept. 1, 1937.

<sup>2</sup> Fractional distillation (or rectification) is the general process for separating liquids of somewhat different boiling points which occur together in solution by repeatedly evaporating and condensing portions of the mixtures.

pentane, liquefied together, began to find a market; but it was not long before the advantages of a complete separation of the gases, and their marketing as separate products, became apparent. This complete separation is also accomplished by fractional distillation.

**Sources of Supply.** Much of the liquefied fuel gas still comes from natural gas, although oil refineries constitute their greatest potential source. The total quantity which could be obtained from these sources is said to be very great and to be much in excess of any possible demand for domestic use other than house heating.

**Table 9-32. Physical Properties of Light Hydrocarbons<sup>1</sup>**

(Exclusive of combustion data which are shown in Table 9-33)

	Methane	Ethane	Propane	Iso-butane	Butane	Pentane
Molecular volume of gas, cu ft <sup>a</sup> . . . . .	378 7	375 8	372 7	366 7	365 4	
Molecular weight of gas . . . . .	16 04	30 07	44 09	58 12	58.12	72.15
Gal/lb-mol at 60°F . . . . .	6 4 <sup>b</sup>	9 64	10 41	12 38	11.94	13.71
Weight:						
Per cent carbon . . . . .	74 88	79 88	81 72	82 66	82.66	
Per cent hydrogen . . . . .	25 12	20 12	18 28	17.34	17.34	
Specific gravity:						
Of liquid (water = 1) . . . . .	0 248	0.377	0.508	0 563	0 584	0 631
Of liquid, deg API. . . . .	340 <sup>b</sup>	247	147	120	111	93
Of gas (air = 1) . . . . .	0 555	1 048	1 550	2.077	2.084	2 490
Weights and volumes:						
Lb/gal of liquid . . . . .	2 5 <sup>b</sup>	3 145	4 235	4 694	4.873	5.250
Cu ft of gas/gal of liquid. . . . .	59 0 <sup>b</sup>	39 69	36 28	30.65	31 46	27.67
Cu ft of gas/lb of liquid . . . . .	24 8	12 50	8 55	6 50	6.50	
Ratio, gas volume to liquid volume <sup>c</sup> . . . . .	443 <sup>b</sup>	293 4	272 7	229.3	237.8	207.0
Initial boiling point (atmospheric pressure) . . . . .	-259	-128 2	-43.7	10.9	31.1	97
Heat value (gross)						
Btu/cu ft of gas . . . . .	1,012	1,786	2,522	3,163	3,261	4,023
Btu/lb of liquid. . . . .	23,885	22,323	21,560	20,732	21,180	21,110
Btu/gal of liquid . . . . .		70,210	91,500	103,750	102,600	110,800
Vapor pressure, psia:						
At -44°F. . . . .		88	0	-9	-12	-14
At 0°F . . . . .		206	38	12	-7	-13
At 33°F . . . . .		343	54	17	0	-11
At 70°F . . . . .		563	124	45	31	-6
At 90°F . . . . .		710	165	62	44	
At 100°F . . . . .			189	72	52	4
At 130°F . . . . .			275	110	81	11
At 150°F . . . . .			346	138	87	21
Latent heat of vaporization at boiling point:						
Btu/lb . . . . .	221	211	185	158	167	153
Btu/gal . . . . .	553	664	785	742	808	802
Specific heat:						
Of liquid, at C <sub>p</sub> and 60°F, Btu/lb/°F . . . . .		0 780	0 588	0 560	0 549	
Of gas, at C <sub>p</sub> and 60°F, Btu/lb/°F . . . . .	0 526	0 413	0 390	0 406	0.396	0.402
Of gas, at C <sub>v</sub> and 60°F, Btu/lb/°F. . . . .	0 402	0 347	0 346	0.373	0.363	0 376

<sup>1</sup> From various sources, principally "Gaseous Fuels," AGA, 1948; "Handbook Butane-Propane Gases," Western Business Papers, Los Angeles, 1945; Propane, Butane, and Related Fuels, *NBS (U.S.) Letter Circ.* 503.

<sup>a</sup> Ideal gas = 379.5 cu ft.

<sup>b</sup> Apparent values for dissolved methane at 60°F.

<sup>c</sup> Based on "perfect gas."

### Petroleum Gases

Natural gas and petroleum as they occur in nature consist of mixtures of many substances. These are chiefly hydrocarbons, of which the predominant "family" is the "saturated series." The compositions of these vary in a regular manner, the first six members being the following: methane,  $\text{CH}_4$ ; ethane,  $\text{C}_2\text{H}_6$ ; propane,  $\text{C}_3\text{H}_8$ ; butane,  $\text{C}_4\text{H}_{10}$ ; pentane,  $\text{C}_5\text{H}_{12}$ ; and hexane,  $\text{C}_6\text{H}_{14}$ . In the case of butane and higher members of the series, different arrangements of the atoms in the molecules are possible and cause slightly different properties. There are two butanes and three pentanes. Ordinarily these different "isomers" are not separated, the only common exception being that "isobutane" is frequently separated from "normal butane."

**Properties of Petroleum Gases.** The properties of the hydrocarbons which are of the most importance in connection with their use as fuels are given in Table 9-32. In this table, heating values in Btu per pound are computed from the heats of combustion per mol with 12.01 as the atomic weight of carbon. The heating values (in Btu per cubic foot) and specific gravity of the vapors, except those of pentane, have been corrected for deviation from the ideal gas law at 60°F and 1 atm. Pentane is a liquid at 60°F, but its concentration in gas mixtures, even those in which it is the only fuel, is usually low, and it has been assigned the heating value and specific gravity corresponding to an ideal gas. The vapor pressures given were obtained graphically from plots of various vapor-pressure data.

**Table 9-33. Combustion Data of Light Hydrocarbons<sup>1</sup>**

	Methane	Ethane	Propane	Iso-butane	Butane	Pentane
Ultimate $\text{CO}_2$ in flue products, per cent	11.7	13.1	13.7	.	14.0	14.2
Required for complete combustion:						
Cu ft $\text{O}_2$ /cu ft gas	2.0	3.5	5.0	6.5	6.5	8.0
Cu ft air/cu ft gas	9.55	16.70	23.86	31.02	31.02	38.19
Lb $\text{O}_2$ /lb gas	3.98	3.73	3.63	3.58	3.58	3.54
Lb air/lb gas	17.24	16.13	15.71	15.49	15.49	15.35
Products of combustion:						
Cu ft $\text{CO}_2$ /cu ft gas burned	1.0	2.0	3.0	4.0	4.0	5.0
Cu ft water vapor/cu ft gas burned	2.0	3.0	4.0	5.0	5.0	6.0
Cu ft nitrogen/cu ft gas burned	7.55	13.20	18.86	24.52	24.52	30.19
Lb $\text{CO}_2$ /lb gas burned	2.74	2.92	2.99	3.03	3.03	3.05
Lb water vapor/lb gas burned	2.24	1.79	1.63	1.55	1.55	1.50
Lb nitrogen/lb gas burned	13.26	12.40	12.08	11.91	11.91	11.80
Maximum flame temp in air:						
Observed temp, deg F	3416	3443	3497	3452	3443	
Per cent gas for max temp:						
Min	9.45	5.70	4.05	3.15	3.15	
Max	10.10	5.95	4.30	3.25	3.40	
Ignition temp in air, deg F	1202	986	932	950	896	
Flash temp, deg F (calculated)	-306	-211	-156	-117	-101	
Maximum flame propagation:						
In./sec.	26	34	33.4	33	34.3	
Per cent of gas in mixture	9.5-10	5.7-6	4-4.3	3.6-3.8	3.6-3.8	
Limits of inflammability in air:						
Lower limit (per cent gas in mixture)	5.0	3.2	2.4	1.8	1.9	
Higher limit (per cent gas in mixture)	15.0	12.5	9.5	8.4	8.4	

<sup>1</sup> From various sources, principally "Gaseous Fuels," AGA, 1945; *NBS (U.S.) Letter Circ.* 503; and "Handbook Butane and Propane Gases," 3d ed., Western Business Papers, Los Angeles, 1948. Many of the values in this table are subject to slight variation according to the researcher, date of research, and exact purity of gas used.

### Characteristics, Properties, and Uses of Petroleum Gases

**Methane** is the principal constituent of the vast quantities of natural gas distributed from the wells through pipes and is a so-called "permanent gas," meaning that, at ordinary temperatures, it cannot be liquefied by pressure.

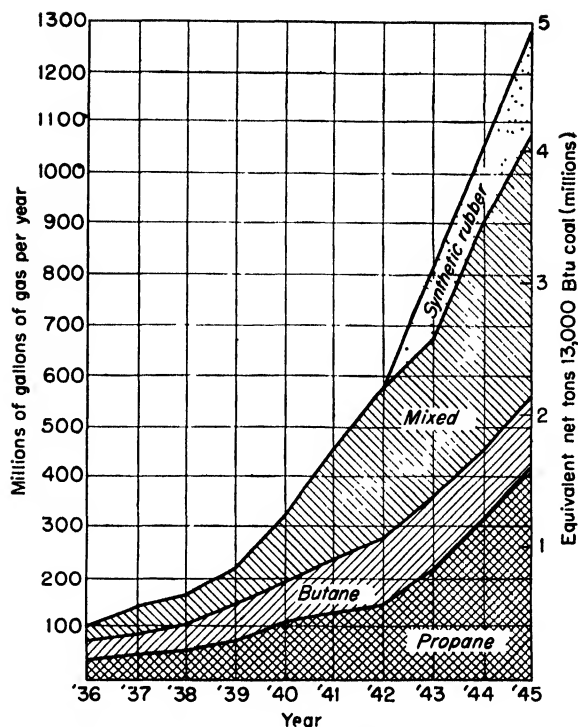


Fig. 9-12. Sales of liquefied petroleum gas, 1936 to 1945, in millions of gallons.

Table 9-34. Sale of Liquefied Petroleum Gases by Uses in 1948<sup>1</sup>

Principal uses	Butane		Propane		Butane-propane mix		Total LPG	
	Thou-sand gal	Per cent	Thou-sand gal	Per cent	Thou-sand gal	Per cent	Thou-sand gal	Per cent
Domestic and commercial..	113,001	22.0	765,953	59.9	594,335	62.9	1,473,289	53.8
Gas manufacturing	63,572	12.4	133,175	10.4	40,991	4.4	237,638	8.7
Industrial plants	66,486	13.0	112,290	8.8	35,128	3.7	213,904	7.8
Synthetic rubber	194,777	38.0	4,125	0.3	26,739	2.8	225,641	8.3
Chemical plants	54,386	10.6	249,653	19.5	186,925	19.8	490,964	17.9
Internal combustion	20,019	3.9	14,132	1.1	58,790	6.2	92,941	3.4
All other uses . . . . .	374	0.1	516	...	1,534	0.2	2,424	0.1
Total U.S. sales	512,615	100.0	1,279,744	100.0	944,442	100.0	2,736,801	100.0
Percentage change since 1947 . . . . .		+28.6		+48.2		-0.3		+23.8

<sup>1</sup> U.S. Bureau of Mines Mineral Market Report, mms. 1760, July 27, 1949.

**Ethane** can be liquefied by pressure alone at temperatures as high as 90°F, but if metal containers are to be filled with the liquid they must be of excessively heavy construction. Ethane is therefore seldom distributed alone and is of importance in this section only insofar as its presence in solution in propane and butane affects their properties. The presence of even small amounts of ethane in either propane or butane may cause a great deal of trouble from backfiring (flashing back) or blowing from the burner ports, particularly when a fresh cylinder of gas is started.

**Propane** is a gas at atmospheric pressure at all temperatures above  $-44^{\circ}\text{F}$  but can be liquefied at moderate pressure and is safe in a container of moderate strength. It is thus in great demand as a fuel, especially for tank or "bottle" service. In 1946, 41 per cent of the domestic fuel thus sold was propane and an additional 53 per cent mixtures of propane and butane. Of liquefied petroleum fuels sold for all purposes in 1946, propane constituted 32.2 per cent and propane-butane mixtures 42.1 per cent.

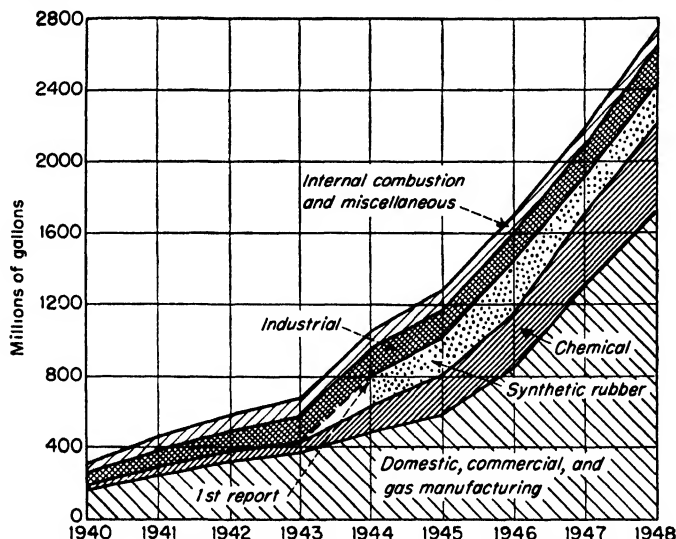


Fig. 9-13. Sales of liquefied petroleum gas by principal uses.

Table 9-35. Combustion Data of Hydrocarbons<sup>1</sup>

Hydrocarbon	Ultimate CO <sub>2</sub> , per cent	Cu ft required/cu ft gas or vapor for combustion		Products of combustion, cu ft formed by burning 1 cu ft			Lb required for combustion 1 lb gas or vapor		Products of combustion, lb from burning 1 lb of gas or vapor		
		Air	O <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	N	Air	O <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	N <sub>2</sub>
Methane CH <sub>4</sub> .....	11.7	9.55	2.0	1.0	2.0	7.55	17.24	3.98	2.74	2.24	13.26
Ethane C <sub>2</sub> H <sub>6</sub> .....	13.1	16.70	3.5	2.0	3.0	13.20	16.13	3.73	2.92	1.79	12.40
Propane C <sub>3</sub> H <sub>8</sub> .....	13.7	23.86	5.0	3.0	4.0	18.86	15.71	3.63	2.99	1.63	12.08
Butane C <sub>4</sub> H <sub>10</sub> .....	14.0	31.02	6.5	4.0	5.0	24.52	15.49	3.58	3.03	1.55	11.91
Pentane C <sub>5</sub> H <sub>12</sub> .....	14.2	38.19	8.0	5.0	6.0	30.19	15.35	3.54	3.05	1.50	11.80
Ethylene C <sub>2</sub> H <sub>4</sub> .....	15.0	14.32	3.0	2.0	2.0	11.31	14.80	3.42	3.13	1.28	11.38
Propylene C <sub>3</sub> H <sub>6</sub> .....	15.0	21.48	4.5	3.0	3.0	16.98	14.80	3.42	3.13	1.28	11.38
Butylene C <sub>4</sub> H <sub>8</sub> .....	15.0	28.58	6.0	4.0	4.0	22.58	14.80	3.42	3.13	1.28	11.38

<sup>1</sup> "Handbook Butane-Propane Gases," 5th ed., p. 32, Western Business Papers, Los Angeles, 1945.

Under practically all probable conditions of domestic use, a cylinder of liquid propane will deliver a continuous supply of gas at a pressure ample for its effective utilization.

**Normal butane** boils at  $33^{\circ}\text{F}$  and, since its evaporation cools it somewhat, its liquid cannot be made to supply gas at a satisfactory pressure unless the surroundings of the container are at a temperature considerably above that point. Butane is therefore seldom used for domestic purposes, except in the South where it is usually stored underground in order that the heat for vaporization may be obtained from the ground in the colder weather. There it is extensively used, especially in the sparsely

**Table 9-36. Tentative NGAA<sup>a</sup> Liquefied Petroleum Gas Specifications**

	Commercial propane	Commercial butane	Butane-propane mixtures
Definition	Commercial propane shall be a hydrocarbon product composed predominantly of propane and/or propylene and shall be free from harmful quantities of deleterious substances	Commercial butane shall be a hydrocarbon product composed predominantly of butane and/or butylenes and shall be free from harmful quantities of deleterious substances	Butane-propane mixtures shall be hydrocarbon products composed predominantly of mixtures of butane and/or butylenes with propane and/or propylene and shall be free from harmful quantities of deleterious substances
Composition	The composition of commercial propane shall be at least 95% propane and/or propylene by liquid volume as determined by the combined results of the vapor-pressure and mercury-freezing tests	No specification	No specification
Mercury freezing test	The residue as determined by the mercury-freezing test shall not be more than 2% by volume	No specification	No specification
Vapor pressure	The vapor pressure at 105°F as determined by the liquefied petroleum gas vapor-pressure method shall not be in excess of 225 psi	The vapor pressure at 105°F as determined by the liquefied petroleum gas vapor-pressure method shall not be in excess of 75 psi	The vapor pressure at 105°F as determined by the liquefied petroleum gas vapor-pressure method shall not be in excess of 225 psi
Sulphur content	The product shall be free of hydrogen sulphide and shall not contain mercaptans or sulphur compounds of a corrosive nature. The unattended produce shall not contain total sulphur in excess of 15 grains per hundred cu ft of vapor as determined by the test for total sulphur in liquefied petroleum gases		
Water content...	The product shall satisfactorily pass the standard cobalt bromide test	The product shall be free of mechanically entrained water	The product shall be free of mechanically entrained water
Odorization.....	A sufficient quantity of an odorizing agent of such character as to indicate positively the presence of gas down to concentrations in air of not over one-fifth the lower limit of flammability by a distinctive odor shall be added by the manufacturer		
95% boiling point	No specification	The quantity evaporated at a temperature of 34°F corrected to a barometric pressure of 740 mm Hg, shall be 95% or more by volume, as determined by the open-cylinder weathering test	
Product designation	No specification	No specification	Butane-propane mixtures shall be designated by the vapor pressure at 100°F in psi. To comply with the designation the vapor pressure of the mixtures shall be within +0, -5 lb of the vapor pressure specified. For example, a product specified as 95 lb liquefied petroleum gas shall have a vapor pressure of at least 90 lb but not exceeding 95 lb

<sup>a</sup> National Gasoline Association of America, Tulsa, Okla. A pamphlet containing specifications and test methods is available.

Table 9-37. CNGA<sup>1</sup> Liquefied Petroleum Gas Specifications

CNGA standard grade	A	B	C	D	E	F
Max range of vapor pressures, psi at 100°F <sup>a</sup> .....	80	100	125	150	175	200
Range of allowable specific gravities, 60°/60°F	0.585-0.555	0.560-0.545	0.550-0.535	0.540-0.525	0.530-0.510	0.520-0.504
Composition <sup>b</sup> .	Predominately butanes	Butane-propane mixtures. Largely butane	Butane-propane mixtures. Proportions approximately equal	Butane-propane mixture. Propane exceeds butane	Propane-butane mixture. Largely propane	Predominantly propane
Residue and 90 per cent evaporated temperature	The residue of any liquefied petroleum gas shall not be greater than 3 %. The 90 % evaporated temperature shall be stated with an accuracy of $\pm 2.5^{\circ}\text{F}$					
Sulphur content .	The liquefied petroleum gases shall contain no corrosive form of sulphur such as hydrogen sulphide or highly reactive mercaptans					
Water and other contaminants	Liquefied gases shall contain no mechanically entrained water or other contaminants					
Odorization.. . .	Every liquefied petroleum gas sold shall be so odorized by an agent of such offensiveness that the presence of such odorized gas in air shall be positively indicated when its concentration therein exceeds one-fifth of the concentration at the lower limit of inflammability of such gas, except that such odorant shall not be required where it will interfere seriously with a specific industrial use					

<sup>1</sup> California Natural Gasoline Association, Los Angeles, Calif. Tentative standard test methods covering tests mentioned in the above specifications are available in pamphlet form.

<sup>a</sup> The actual vapor pressure at 100°F of the product may, in order to provide a manufacturing tolerance, be 5 per cent under the stated pressure, but in no event shall the actual vapor pressure exceed the stated vapor pressure.

<sup>b</sup> When olefin constituents are components of the liquefied petroleum gas mixture, "butanes and butylenes" and "propane and propylene" should be understood, where applicable, instead of "butanes" and "propanes," respectively.

settled areas, because its low vapor pressure makes its delivery much less expensive than that of propane. The principal use for straight butane (61 per cent in 1946) is in the manufacture of synthetic rubber.

**Isobutane** is somewhat more volatile than normal butane, with a boiling point of 14°F as compared with 33°F.

**Pentane**, because of its high boiling point (97°F), can be used for supplying gas to individual dwellings only through such expedients as passing air under pressure through the pentane container and burning the resultant mixture of air and pentane vapor. This is sometimes accomplished by bubbling air through the liquid and sometimes by passing it over the surfaces which may be increased by wicks or their equivalent. Aside from this complication, such systems have the disadvantage of a variability of the mixture with variations in the temperature of the pentane. Usually the pentane tank is buried deeply in the ground to reduce temperature changes, and several systems have devices for adding controlled amounts of air to produce mixtures of greater uniformity than that obtained by vaporization alone.

Such pentane systems are essentially the same as the systems for supplying **air saturated with gasoline** which have been used in many places for 50 years or more. Old plants of this type can be used with pentane with an improvement in the constancy of the gas supplied. If the substitution of pentane is made, appliances will generally have to be readjusted to take more air into the burner because of the greater proportion of fuel in the mixture supplied to the burner.

**Hexane**, a liquid boiling at 156°F, is one of the important constituents of ordinary gasoline. Gasoline itself is a mixture containing, in the main, still higher members

of the methane series of hydrocarbons, but also much hexane and appreciable amounts of pentane.

Propylene and butylene are often associated with propane and butane from which they are not easily separated by distillation. The properties of propylene and butylene which affect their use as fuels are nearly the same as the corresponding properties of propane and butane; hence they are not always separated, in which case the liquid gases from refineries will contain both series of hydrocarbons. They have strong odors, and a moderate amount of them is frequently added to propane and butane to make the detection of leaks easier and to serve as a warning.

Table 9-38. Typical Analyses of Propane and Butane<sup>1</sup>

	Propane		Butane		Butane-air mix
	Natural gas	Refinery gas	Natural gas	Refinery gas	
Constituents, per cent by volume:					
Ethane (C <sub>2</sub> H <sub>6</sub> ) . . .	2 2	2 0			
Propane (C <sub>3</sub> H <sub>8</sub> ) . . .	97 3	72.9	6 0	5 0	
Butane (C <sub>4</sub> H <sub>10</sub> ) . . .	0 5	0.8	94 0 <sup>a</sup>	66 7 <sup>b</sup>	17 2
Propylene (C <sub>3</sub> H <sub>6</sub> ) . . .		24 3			
Butylene (C <sub>4</sub> H <sub>6</sub> ) . . .				28.3	
Air . . . . .					82 8
Sp gr . . . . .	1 55	1 77	2 04	2 00	1.16
Btu:					
Gross . . . . .	2,558	2,504	3,210	3,184	550
Net . . . . .	2,358	2,316	2,961	2,935	516

<sup>1</sup> "Gaseous Fuels," p. 32, AGA, New York, 1948.

<sup>a</sup> 16.5 per cent isobutane; 50.1 per cent *n*-butane.

<sup>b</sup> 23.3 per cent isobutane; 70.7 per cent *n*-butane.

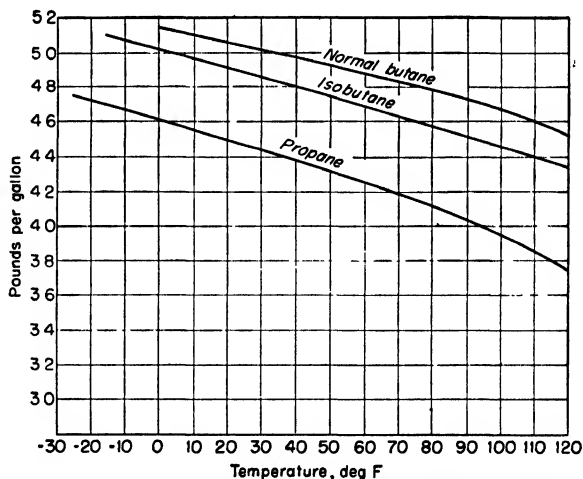


FIG. 9-14. Weight per gallon of liquefied petroleum gases at various temperatures. ("Handbook Butane-Propane Gases," 1948.)

#### Use of Mixed Liquefied Petroleum Gases

Fuel gases which have not been completely separated into their constituents, but remain mixtures, are practically as useful for enrichment of manufactured-gas sup-



plies as are pure hydrocarbons, but their use for domestic supplies involves considerable difficulty. If such mixtures are allowed to evaporate in the cylinders, the gas first delivered is mainly the lowest boiling substance present in appreciable quantity; that delivered when the cylinder is nearly discharged is mainly the highest boiling substance. Such a variation in composition is too great to permit the satisfactory adjustment of appliances; hence liquid mixtures of this character are taken from the bottom of the container and vaporized in the line to the burner, usually in a specially arranged vaporizer which is sometimes heated by the burner itself, sometimes only by indoor air. No appreciable change in composition then results during the discharge

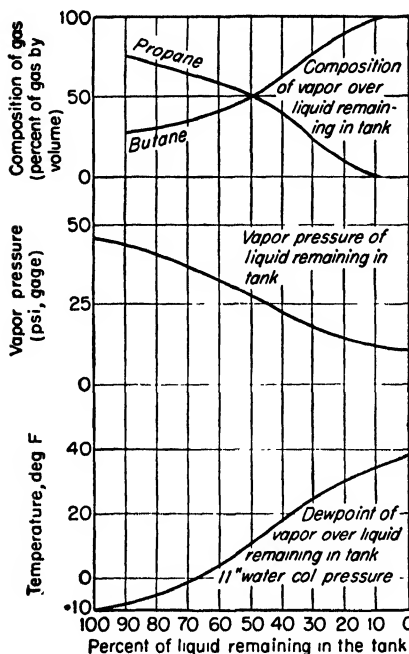


FIG. 9-15. Batch evaporation of a mixture of 60 per cent normal butane and 40 per cent propane by volume. (E. W. Evans, Phillips Petroleum Co., in "Handbook of Butane-Propane Gases," 1948.)

of the cylinder. A mixture of this kind may contain enough ethane and propane to give a satisfactory working pressure. Otherwise, the pressure may be supplied by pumping air into the supply tank. At the best, a system supplied for a mixture cannot be regarded as being as satisfactory as a supply of commercially pure propane, although lower cost may justify its use.

In some cases different mixtures have been supplied in summer and winter to more nearly equalize the pressure of the supply at the different seasons. When this is done, a considerable change in the conditions of combustion is unavoidable, and readjustments of the appliances may be required for satisfactory service.

#### Use of Liquefied Petroleum Gases by Utilities<sup>1</sup>

If the appliances in use are properly designed for burning propane, and if the cost of the raw fuel can be justified, it is an ideal gas for a public supply, particularly in a small town. The equipment required at the distributing station is extremely simple and, with the exception of the tank in which the liquid propane is stored, very inexpensive. Practically no

labor or attendance is required in connection with production, since the vaporization of the liquid takes place automatically to meet any demand. Distribution is also simple and economical. No holder is needed, there is no condensation and no corrosion in the mains, and the high heating value permits the distribution of the same amount of fuel through the same system with only about 11 per cent of the variation of pressure that would be involved in the distribution of average manufactured gas. The product is of uniform composition, which, with uniform pressure, minimizes appliance adjustments.

Plants for sending out mixtures of butane and air are also nearly automatic but require some power-driven machinery, demand more attention, and possess more possibilities for trouble than a propane system.

<sup>1</sup> Propane, Butane, and Related Fuels, NBS (U.S.) Letter Circ. 503, Sept. 1, 1937.

**Choice of Liquefied Petroleum Gas Types.** As systems increase in size, from the domestic unit to those which supply large towns, the advantages of propane are of decreasing importance and the high initial cost of propane is of increasing importance. Small systems can therefore use propane more advantageously; for large systems the cost of the liquid hydrocarbon overbalances the superiority of propane in other respects and makes preferable the supplying of butane. For still larger systems the cost of butane becomes prohibitive in comparison with the cost of a manufacturing plant, and one of the older manufacturing processes becomes the most practical.

**Extent of Use by Manufactured-gas Companies.** According to reports of the AGA, liquefied petroleum gas, as of May, 1947, was being delivered through mains to 187,000 customers in 306 communities by 157 companies in 36 states.

Butane-air gas and propane-air gas with heating value ranging from 520 to 1,600 Btu per cu ft was supplied to 238 communities in 35 states.

A mixture of undiluted butane and propane gas with heating value of 2,800 to 3,000 Btu per cu ft was supplied 17 communities in Arizona, California, and New Mexico.

Undiluted propane gas with heating value of 2,515 to 2,575 Btu per cu ft was supplied 51 communities in Maryland, Massachusetts, Minnesota, Missouri, Nebraska, New Jersey, North Carolina, North Dakota, Virginia, and Wisconsin.

**Use for Peak Loads.** The use of liquefied hydrocarbons to supplement manufactured or natural gas during peak demands is very practical where the cost of such storage can be justified. If either propane or butane is in storage, it can be introduced into the supply of the other gas without delay, at a rate equal to considerable plant capacity and with only a very negligible amount of additional labor.

#### Admixture of Air to Liquefied Petroleum Gases

While propane is usually distributed without dilution, it is necessary to add another gas, usually air, to butane in order to prevent condensation in the distributing system and to permit the entrainment of enough primary air in appliances. Unfortunately, there has been a tendency to carry this dilution to a heating value of 520 to 550 Btu, which is much too far.

If a mixture of butane and air of 525 Btu per cu ft is supplied to an appliance adjusted for a coal gas of the same heating value, at such a pressure as to deliver the same cubic feet and heat units, the total air in the primary mixture will be about twice as much as is desirable. If the burners are adjusted for typical natural gas, the amount of air injected will be about 3.5 times the requirements. On the other hand, a 1,000-Btu mixture of butane and air will inject only slightly more air than is needed for best results when supplied to a burner adjusted for 525-Btu coal gas, and 60 per cent more than is needed when supplied to a burner adjusted for typical natural gas.

The large quantity of air delivered with the butane not only results in a troublesome problem in the utilization of the gas with existing appliances but involves expense for its own transmission. Excessive air incurs expense to transmit air from the plant to the burner and additional expense to prevent air already surrounding the burner from entering it.

Actually, to use the same appliance without adjustment for average natural gas and a butane-air mixture, the heating value of the latter should be somewhat above 2,000 Btu per cu ft. However, with the usual adjustments of orifices and air shutters, ordinary appliances will serve for butane-air mixtures of 1,000 to 1,500 Btu.

The properties of butane, other than its ability to inject air, are such as to require, for best results, a burner substantially identical with the best burner for natural gas. Most such appliances are made to meet the standards of the AGA when tested with typical natural and manufactured gases.

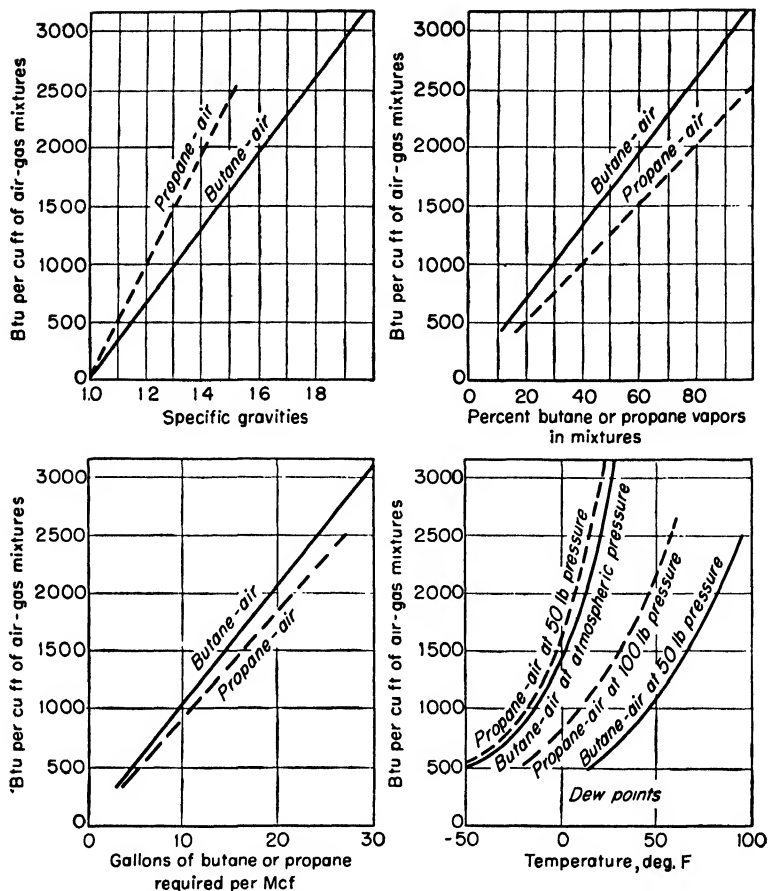


FIG. 9-16. Properties of various Btu propane- and butane-air mixtures. ("Gaseous Fuels," AGA, 1948.)

#### Effect of Impurities in Propane

If the gas is evaporated in the supply tank and drawn from the top, it is essential, that the liquid be propane of fairly high purity. Otherwise, a decided change in composition will result during the discharge of the fuel.

The presence of ethane in even small quantities may cause trouble from backfiring (flashing back) or blowing from the ports when a fresh cylinder is first connected.

The presence of butane will result in improperly aerated flames and incomplete combustion, with production of carbon monoxide in possibly harmful amounts, particularly when the fuel is nearly exhausted.

Using the AGA selected values for the permissible limits of the "index of change of performance of appliances" as a criterion, approximately 35 per cent of one hydrocarbon in the next hydrocarbon of the series should not make necessary a change of adjustment of the appliance. However, this relationship was derived for the permissible limits with the usually variable city supplies. The close adjustment of propane-burning appliances to their optimum condition is the only thing that makes

possible the superior efficiency of propane; hence no such variation as wide as this is compatible with the claims for the superiority of this fuel.

### Filling Liquefied Petroleum Tanks

Pressure containers must never be completely filled with liquid or filled to a point where any normal temperature increase will cause them to be completely filled with liquid. The possibility that a cylinder will become liquid-full from a normal increase in liquid temperature is minimized through the proper use of "filling densities" set up by such authorities as the ICC and National Fire Prevention Association.

**Filling Density.** The "filling density" is defined as the per cent ratio of the weight of the gas in a container to the weight of water the container will hold at 60°F. As

**Table 9-39. ICC and NFPA Maximum Filling Densities and Corresponding Maximum Liquid Content at 60°F for Liquefied Petroleum Gases of Various Specific Gravities**

LPG sp gr at 60°F	Aboveground containers				Underground containers	
	0-1,200 gal		Over 1,200 gals		All capacities	
	Per cent total of water capacity	Max LPG content at 60°F, volume per cent	Per cent total of water capacity	Max LPG content at 60°F, volume per cent	Per cent total of water capacity	Max LPG content at 60°F, volume per cent
0 473-0 480	38	80.4-79 2	41	86.7-85 5	42	88.7-87 5
0 481-0 488	39	81 0-80 0	42	87.3-86 0	43	89 4-88.1
0 489-0 495	40	81 9-80 9	43	88 0-86 9	44	90.0-88.9
0 496-0 503	41	82 6-81 5	44	88 6-87 5	45	90.6-89.5
0 504-0 510	42	83 4-82 4	45	89.4-88.3	46	91.4-90.2
0 511-0 519	43	84.0-83 0	46	89 6-89 1	47	91 9-90.6
0 520-0 527	44	84 6-83 5	47	90.4-89 2	48	92 3-91.1
0 528-0 536	45	85 2-83 9	48	90.9-89 5	49	92 8-91.4
0 537-0 544	46	85 6-84 6	49	91.2-90 1	50	93.0-92.0
0 545-0 552	47	86.2-85 1	50	91.7-90.5	51	93 5-92.3
0 553-0 560	48	86.8-85 7	51	92 2-91 1	52	94 0-92.9
0 561-0 568	49	87 3-86 3	52	92.6-91.6	53	94 4-93.4
0 569-0 576	50	87 9-86.7	53	93.1-91.9	54	94 9-93.7
0 577-0 584	51	88 4-87 4	54	93.6-92.5	55	95 3-94.2
0 585-0 592	52	88.9-87.8	55	94.0-92.9	56	95.8-94.5
0 593-0 600	53	89.4-88.3	56	94.4-93 3	57	96.1-95.0
0 601-0 608	54	89 7-88.8	57	94.7-93 8	58	96 4-95.4
0 609-0 617	55	90 4-89.1	58	95 3-94 0	59	96 9-95.6
0 618-0 626	56	90 6-89.6	59	95 5-94 4	60	97.1-96.0
0 627-0 634	57	90.9-89 9	60	95 7-94 7	61	97 3-96.2

applied to liquefied petroleum gas, the Interstate Commerce Commission has specified that "the liquid portion of the gas in an unlagged container shall not completely fill the container at 130°F, and in the case of lagged containers and underground containers shall not be liquid full at 105°F." The accepted code for both above- and underground containers is shown as Table 9-39. Additional similar codes are available for other types of tanks, such as tank cars.

**Use of Filling-density Tables.** Filling-density tables show the permissible filling densities for the specific container for which the table applies, as corresponding to the gravity of the filling material. This filling-density figure must be converted to volume

for practical use. This is accomplished by dividing the proper filling-density value by the corresponding specific-gravity value at the filling temperature.

**Example.** If the specific gravity of the material is 0.520 at 60°F and the corresponding filling density from the proper table is 44 per cent, the maximum volume at 60°F which may be placed in the tank is determined by dividing 44 by 0.520. In this instance, the tank can be safely filled to 84.6 per cent of its liquid capacity.

Table 9-39 shows both the filling density in per cent of water capacity and the corresponding maximum liquefied petroleum gas content, for the types of tanks

**Table 9-40. Liquid Volume Correction Factors (NGAA, 1942)**

Observed temp, deg F	Specific gravities at 60°/60°F														
	0.500	Pro- pane 0.5079	0.510	0.520	0.530	0.540	0.550	0.560	Iso- butane 0.5631	0.570	0.580	n-Bu- tane 0.5844	0.590	0.600	n-Pen- tane 0.6310
-50	1 160	1 155	1 153	1 146	1 140	1 133	1 127	1 122	1 120	1 116	1 111	1 108	1 106	1 102	
-40	1 147	1 142	1 140	1 134	1 128	1 122	1 117	1 111	1 110	1 106	1 101	1 099	1 097	1 093	
-30	1 134	1 129	1 128	1 122	1 116	1 111	1 106	1 101	1 100	1 096	1 092	1 090	1 088	1 084	
-20	1 120	1 115	1 114	1 109	1 104	1 099	1 095	1 090	1 089	1 086	1 082	1 080	1 079	1 076	
-10	1 105	1 102	1 100	1 095	1 091	1 087	1 083	1 079	1 078	1 075	1 072	1 071	1 069	1 066	
0	1 092	1 088	1 088	1 084	1 080	1 076	1 073	1 069	1 068	1 066	1 063	1 062	1 061	1 058	1 051
4	1 086	1 083	1 082	1 079	1 075	1 071	1 068	1 065	1 064	1 062	1 059	1 058	1 057	1 054	1 048
8	1 081	1 078	1 077	1 074	1 070	1 066	1 063	1 060	1 059	1 057	1 055	1 053	1 052	1 050	1 045
12	1 075	1 072	1 071	1 068	1 064	1 061	1 059	1 056	1 055	1 053	1 051	1 049	1 048	1 046	1 041
16	1 070	1 067	1 066	1 063	1 060	1 056	1 054	1 051	1 050	1 048	1 046	1 045	1 044	1 043	1 038
20	1 064	1 062	1 061	1 058	1 054	1 051	1 049	1 046	1 046	1 044	1 042	1 041	1 040	1 039	1 034
24	1 058	1 056	1 055	1 052	1 049	1 046	1 044	1 042	1 042	1 040	1 038	1 037	1 036	1 034	1 031
28	1 052	1 050	1 049	1 047	1 044	1 041	1 039	1 037	1 037	1 035	1 034	1 034	1 032	1 031	1 028
32	1 046	1 044	1 043	1 041	1 038	1 036	1 035	1 033	1 033	1 031	1 030	1 030	1 028	1 027	1 024
36	1 039	1 038	1 037	1 035	1 033	1 031	1 030	1 028	1 028	1 027	1 025	1 025	1 024	1 023	1 021
40	1 033	1 032	1 031	1 029	1 028	1 026	1 025	1 024	1 023	1 023	1 021	1 021	1 020	1 019	1 017
44	1 027	1 026	1 025	1 023	1 022	1 021	1 020	1 019	1 019	1 018	1 017	1 017	1 016	1 016	1 014
48	1 020	1 019	1 019	1 018	1 017	1 016	1 015	1 014	1 014	1 013	1 013	1 013	1 012	1 012	1 011
52	1 014	1 013	1 012	1 012	1 011	1 010	1 010	1 009	1 009	1 009	1 009	1 009	1 008	1 008	1 007
56	1 007	1 007	1 006	1 006	1 005	1 005	1 005	1 005	1 005	1 005	1 004	1 004	1 004	1 004	1 003
60	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000
64	0 993	0 993	0 994	0 994	0 994	0 994	0 995	0 995	0 995	0 995	0 995	0 996	0 996	0 996	0 996
68	0 986	0 986	0 987	0 987	0 988	0 989	0 990	0 990	0 990	0 990	0 991	0 991	0 991	0 992	0 993
72	0 979	0 980	0 981	0 981	0 982	0 983	0 984	0 985	0 986	0 986	0 987	0 987	0 987	0 988	0 989
74	0 976	0 976	0 977	0 978	0 980	0 980	0 982	0 983	0 983	0 984	0 985	0 985	0 985	0 986	0 987
76	0 972	0 973	0 974	0 975	0 977	0 978	0 979	0 980	0 981	0 982	0 982	0 982	0 983	0 984	0 986
80	0 965	0 967	0 967	0 969	0 971	0 972	0 974	0 975	0 976	0 977	0 978	0 978	0 979	0 980	0 982
84	0 957	0 959	0 960	0 962	0 965	0 966	0 968	0 970	0 971	0 972	0 974	0 974	0 974	0 976	0 979
88	0 950	0 952	0 953	0 955	0 958	0 961	0 963	0 965	0 966	0 967	0 969	0 969	0 970	0 971	0 976
92	0 942	0 945	0 946	0 949	0 952	0 955	0 957	0 959	0 960	0 962	0 964	0 965	0 966	0 967	0 972
96	0 935	0 938	0 939	0 942	0 946	0 949	0 952	0 954	0 955	0 957	0 959	0 960	0 961	0 963	0 970
100	0 927	0 930	0 932	0 936	0 940	0 943	0 946	0 949	0 950	0 952	0 954	0 955	0 957	0 959	0 964
105	0 917	0 920	0 923	0 927	0 931	0 935	0 939	0 943	0 943	0 946	0 949	0 949	0 951	0 954	
110	0 907	0 911	0 913	0 918	0 923	0 927	0 932	0 936	0 937	0 939	0 943	0 944	0 946	0 949	
115	0 897	0 902	0 904	0 909	0 915	0 920	0 925	0 930	0 930	0 933	0 937	0 938	0 940	0 944	
120	0 887	0 892	0 894	0 900	0 907	0 912	0 918	0 923	0 924	0 927	0 931	0 932	0 934	0 938	
125	0 876	0 881	0 884	0 890	0 898	0 903	0 909	0 916	0 916	0 920	0 925	0 927	0 928	0 933	
130	0 865	0 871	0 873	0 880	0 888	0 895	0 901	0 908	0 909	0 913	0 918	0 921	0 923	0 927	
135	0 854	0 861	0 863	0 871	0 879	0 887	0 894	0 901	0 902	0 907	0 912	0 914	0 916	0 921	
140	0 842	0 850	0 852	0 861	0 870	0 879	0 886	0 893	0 895	0 900	0 905	0 907	0 910	0 915	

specified. However, it is important to note the necessity for correcting gas volumes to 60°F. This results in the following formula:

1. *Formula for calculating the maximum allowable volume of liquefied petroleum gas which can be placed in a container.*

$$V = \frac{A \times F}{S \times C \times 100}$$

where  $V$  = maximum allowable volume, gal, of liquefied petroleum gas at temperature  $T^\circ\text{F}$

$A$  = water capacity of tank at 60°F, gal

$F$  = filling density, per cent, from tables

$S$  = specific gravity of liquefied petroleum gas at 60°F

$C$  = temperature correction factor from temperature  $T^\circ\text{F}$  to 60°F

2. *Alternate method of calculating the maximum permissible volume which can be placed in a tank.*

1 gal of water weighs 8.32828 lb.

Given a tank of 10,000 gal capacity, the water-weight capacity of this tank would be 83,282.8 lb.

Given a material of specific gravity of 0.520 and a corresponding filling density (from table) of 44.0 per cent,  $83,282.8 \times 0.44 = 36,644.4$ , the maximum weight of 0.520 specific gravity material which can be placed in the tank.

The weight of 1 gal of this material at 60°F is  $8.3282 \times 0.520$ , or 4.3307 lb.

$36,644.4 / 4.3307 = 8,460$  gal, the maximum number of gallons of liquefied petroleum gas of 0.520 specific gravity at 60°F that can be placed in tank.

Since this is a 10,000-gal tank, then  $8,460 / 10,000 = 84.6$  per cent of the tank's volume which can be filled.

NOTE: If the liquefied petroleum gas is other than at 60°F, a correction must be made for the difference in volume in filling.

### Storing and Using Liquefied Petroleum Gas<sup>1</sup>

As liquefied petroleum gases are highly inflammable and highly explosive, their correct handling and use should be thoroughly understood before any installation is attempted.

**Transportation.** There are several reasons why transportation accidents involving liquefied petroleum gases can be more disastrous than those involving the transportation of gasoline or other petroleum products. In the transportation of most petroleum products, the liquids are under very little pressure; while in the transportation of liquefied petroleum gases pressures as high as 220 psi (propane) have been reported. Such pressures increase the likelihood of rupture in case of collision.

Spilled liquefied petroleum rapidly vaporizes and mixes with air to form an explosive mixture. If released in large quantities, even in open air, they expand rapidly in all directions, with the chance of ignition from even distant points (200 ft in the case of the Dennison, Tex., explosion of November, 1944). Once ignited, the area affected may be extensive, with an explosive force almost as violent as if confined. One gallon of liquefied petroleum liquid, when released into the air, will produce 250 gal of gas at atmospheric pressure; when this is mixed with air at the explosive range, between 2,500 and 5,000 gal of explosive mixture will be formed.

**Precautions in Domestic Use.** Liquefied petroleum gases are normally under greater pressure in house piping than is usual for natural or manufactured gas; they form explosive mixtures in much smaller proportions with air; and the fact that they are heavier than air prevents their ready escape from a room. A leak so small that

<sup>1</sup> Propane, Butane, and Related Fuels, NBS (U.S.) Letter Circ. 503, Sept. 1, 1937.

it would be ignored if manufactured gas were used is therefore hazardous. For this reason an ordinary job of "gas fitting" will not do. It is preferable to use seamless metal tubing in a single piece from the supply outside the building to the appliance, if possible (copper is generally used). Regulators and pressure reliefs, if used, should be vented to a point from which a gas that flows downward will be least likely to enter the building. The storage containers and all connections must be protected from tampering, from the danger of breakage by ice sliding from the roof, from settling of the building or fuel container, from earthquake or storm damage, from collision with moving vehicles as in a driveway, from grass and trash fires, etc. Connections through which the liquid could be discharged if they were broken should be avoided if possible. If this is not possible, excess flow or reverse-flow check valves should be installed inside the storage container.

**Underground Storage.** Storage underground is particularly hazardous unless elaborate precautions are taken. Underground leaks are hard to detect and repair. The density of the gas makes it tend to remain in underground channels instead of coming to the surface, and basement and foundation walls offer no protection against the entry of gas. Even more serious is the hazard of corrosion of the storage tanks, since liquid can escape through any perforations in the bottom of the tank without reducing the driving pressure through refrigeration as would occur if gas escaped. The resulting spreading blanket of explosive mixture can become a fearful hazard to an entire community. There is no parallel to this in the storage of pentane or gasoline, because they are normally under no pressure, and perforation of the container results, at the worst, in the slow loss of the liquid by capillary filtration through the surrounding soil, which soon tends to become saturated because evaporation can occur only as the heavy vapor is dispersed by diffusion with the immobile atmosphere in the soil.

**Table 9-41. Flow of Butane or Propane through Semirigid Tubing<sup>1</sup>**  
(In thousands of Btu per hour, 0.5 in. pressure drop)

Fuel .. . . . . .	Propane <sup>a</sup>							Butane <sup>b</sup>						
Tubing size, in OD	1/4	3/8	1/2	5/8	3/4	7/8	1	1/4	3/8	1/2	5/8	3/4	7/8	1
Length of pipe, ft														
10	8 7	23	39	92	199	329	501	9 0	40	95	206	341	520	
20	4 3	13	26	62	131	216	346	4 5	27	64	136	224	359	
30	3 0	9 6	21	50	107	181	277	3 1	22	52	111	188	287	
40	...	6.8	19	41	90	145	233	.	20	43	93	151	242	
50	..	...	.	37	79	131	198			39	82	136	206	
60	...	...		35	72	121	187			36	75	126	194	
70	...	...		31	67	112	164			32	70	116	170	
80	...	...		29	62	104	155			30	64	108	161	
90	...	...		27	59	95	146			28	61	98	152	
100	...	...		26	55	90	138	.		27	57	93	143	

<sup>1</sup> "Handbook Butane-Propane Gases," p. 195, Western Business Papers, Los Angeles, 1945.

<sup>a</sup> Propane specific gravity 1.53, 2,500 Btu per cu ft.

<sup>b</sup> Butane specific gravity 2.00, 3,175 Btu per cu ft.

### Units of Sale

Unlike natural and manufactured gas, which are usually measured and sold by the thousands of cubic feet (or by the therm or 100,000 Btu in the case of larger scale use), there is no accepted standard of either measure or sale for liquefied petroleum products. This gives rise to a wide variety of trade units of sale, a few of which are shown in Table 9-43. The National Conference of Weights and Measures is reported to be

**Table 9-42. Selection of Tubing Size for Liquefied Petroleum Gas<sup>1</sup>**

(OD size of copper tubing, type K soft drawn, inches)

Gas load, Btu/hr. ....	10,000	20,000	40,000	60,000	80,000	100,000	150,000	200,000
Gas load, cu ft/hr	4	8	16	24	31	39	59	79
Length of line, ft								
10	1/4	5/16	1/2	1/2	1/2	5/8	5/8	3/4
15	5/16	3/8	1/2	1/2	5/8	5/8	3/4	3/4
20	5/16	3/8	1/2	1/2	5/8	5/8	3/4	3/4
25	5/16	3/8	1/2	5/8	5/8	5/8	3/4	3/4
30	3/8	1/2	5/8	5/8	5/8	5/8	3/4	3/4
40	3/8	1/2	5/8	5/8	5/8	5/8	3/4	3/4
50	3/8	1/2	5/8	5/8	5/8	5/8	3/4	3/4
75	1/2	1/2	5/8	5/8	5/8	5/8	3/4	3/4
100	1/2	1/2	5/8	5/8	5/8	5/8	3/4	3/4
150	1/2	3/4	3/4	3/4	3/4	3/4	1	1

NOTE: Bends must be of sufficient radius to avoid reducing cross-sectional area.

<sup>1</sup> Prepared by Shellane Department of Shell Oil Co.**Table 9-43. A Few Common Units of Sale of Liquefied Petroleum Gas<sup>1</sup>**

Trade Unit of Sale	Reported Equivalent, Cu Ft	Trade Unit of Sale	Reported Equivalent, Cu Ft
On propane meters:		On propane meters:	
Decitherms . . . . .	3 94	Sungas Kiloflames . . . . .	1 35
Decithermus . . . . .	3 85	Vapypre Units . . . . .	0 10
Essotane Units . . . . .	0 85	On butane meters:	
Fast Flame Kiloflames . . . . .	1 35	Decitherms (a) . . . . .	3 07
Happy Cooking Standards	0 85	Decitherms (b) . . . . .	3 125
Kiloflames . . . . .	1 35	Kwhr . . . . .	1 05
Kwhr. . . . .	1 35	Gal . . . . .	32 0
Metered Homegas Units . . . . .	0 21	Therms . . . . .	30 7
Pottergas Units . . . . .	0 21	Lb . . . . .	7 4
Public Gas Kiloflames . . . . .	1 35	On mixed gas meters:	
Pounds . . . . .	8 5	Decitherms . . . . .	4 0
Shorgas Units . . . . .	4 25		

NOTE: 1 cu ft propane contains approximately 2,522 Btu. 1 cu ft butane contains approximately 3,261 Btu.

<sup>1</sup> Based on figures compiled by J. F. Blickley, Director, Bureau of Standard Weights and Measures, Pennsylvania.**Table 9-44. Amount of Propane or Butane Required to Replace Other Fuels**

[Assuming equal combustion efficiencies (see text)]

	Btu	Mfg gas	Natural gas		No. 2 oil	Anthracite	Electricity	
		Mcf	Mcf	Therms	Gal	Tons	Kwhr	Reciprocal
		525,000	1,000,000	100,000	141,800	26,000,000	3,413	*
Propane:								
Lb . .	21,680	24 21	46 12	4 61	6 54	1,200	0 1574	6 35
Therms . .	100,000	5 25	10	1	1 42	260	0 0341	29 30
Gal . . . .	91,900	5 71	10 88	1 09	1 53	283	0 0371	26 93
Mcf . .	2,572,000	0 20	0 39	0 039	0 055	10	0 0013	754
Butane:								
Lb . .	21,330	24 61	46 88	4 69	6 65	1,219	0 1600	6 25
Therms . .	100,000	5 25	10	1	1 42	260	0 0341	29 30
Gal . . . .	103,400	5 08	9 67	0 97	1 37	252	0 0330	30 30
Mcf . .	3,394,000	0 155	0 295	0 03	0 042	7 66	0 0010	994

\* To avoid decimals, the second electrical column is the reciprocal of the first. The figures shown therein thus are the number of kilowatt-hours of electricity required to equal the various gas units as shown at the extreme left. With this exception, the table is used as follows:

**Example** (1) 5.25 therms of propane, at 100,000 Btu, would be required to equal 1,000 cu ft of manufactured gas at 525,000 Btu; or (2) 1,219 lb of butane, at 21,330 Btu, would be required to equal 1 ton of anthracite at 26,000,000 Btu.



studying this matter and further to favor universal measure by volumetric meters and sale in units of cubic feet. It is thus possible that this situation will be changed in the near future.

### Regulations for Liquefied Petroleum Gas Installations

The following rules for the installation of bottled gas cylinders, tanks, and house piping have been published by the Accident Prevention Division of the Association of Casualty and Surety Companies, New York.

#### Cylinders

1. All cylinders should be constructed, tested, maintained, and regularly retested according to the requirements of the Interstate Commerce Commission.

2. Cylinders should be located outside of buildings, aboveground, away from windows and doors. Although accessibility is essential, care should be taken not to place cylinders too near driveways or at "blind" corners where they might be struck by passing vehicles.

3. To avoid the dangers of settling, the cylinder should be set on concrete foundations. Provision should be made for proper drainage of water from and around the foundation to prevent its settlement. The connections from the cylinder to the fixed piping should be of flexible type to prevent breaking of the connections due to foundation settlement, or from the movement of cylinders during replacement, recharging, or weighing operations.

4. All cylinders should be provided with fusible plugs or spring-loaded safety-relief valves or both as required by the Bureau of Explosives. The discharge from these safety devices should be at least 5 ft horizontally away from any building openings which are below the level of such discharges, as, for example, cellar windows. Such discharges should not terminate in any building or beneath any building unless such space is well ventilated to the outside.

5. Cylinder valves, manifolds, and regulator assemblies should be protected from rain, snow, or ice and from being tampered with by children or unauthorized persons. Ventilated metal hoods or cabinets of the lock-up type offer suitable protection against these exposures.

6. The ground around cylinders should be kept free of combustible materials such as long grass, weeds, brush, leaves, and paper to prevent exposure to possible fires from these sources. The burning of rubbish should not be done in the vicinity of cylinders. Other sources of ignition such as electric wires, electrical apparatus, and unprotected electric lights should be kept away from cylinders.

7. The changing or charging of cylinders should be done only in daylight. Open flames, smoking, or the running of motor-vehicle engines in the vicinity should also be prohibited during such operations. If the engine of the truck is being used to operate the liquid pump in the filling operations, the truck should be parked at least 15 ft from the cylinders being filled. If emergencies require cylinders to be charged or changed at night the use of oil or gas lamps or lanterns should be avoided. An Underwriters' Laboratories approved electric flashlight could be used, but it is better to provide a permanent electric light remotely located. All electrical equipment should be approved for *Group D, Class I*, hazardous locations of the *National Electrical Code*. The lights should be so located that the cylinders, regulating valves, and gauging nearby are well illuminated when needed.

8. Cylinders which are recharged at the point of utilization should be provided with excess flow or back-pressure check valves to prevent discharge of the contents of cylinders in event of failure of the filling or equalizing connections. If the contents of such cylinders are not determined by weighing they should be equipped with accurate liquid-level gauging devices approved by the *ICC Regulations*. It is highly

important that the servicemen be cautioned not to fill these cylinders beyond the point indicated by the gauging device.

### Tank Installations

1. Both above- and belowground tanks are employed in domestic installations. Where used, tanks should be constructed and tested in accordance with the requirements of the *ASME* or *ASME-API Codes for Unified Pressure Vessels*.

2. Aboveground tanks should be located away from buildings or the lines of adjoining properties at distances described by *Pamphlet 58 of the National Board of Fire Underwriters* (Table 9-45) or by the governing authorities. When selecting a site, consideration should be given to accessibility so that tanks can be readily serviced from tank trucks. Their location, however, should be such that they are not unduly exposed to passing vehicles.

3. Aboveground tanks should be coated with a reflecting paint.

4. The fire precautions suggested in connection with cylinder installations in paragraphs 6 and 7 above apply also to aboveground tank installations.

5. The first step in deciding upon a site for an underground tank is to locate active or abandoned house drains, sewer mains, and water mains. The tank should not be buried near such underground piping because leakage from the tank or fittings may follow such piping into the buildings.

6. When it is necessary to bury tanks in corrosive soils, the shells and heads should be of thicker metal than in the case of surface tanks. Moreover, if the ground is very corrosive, tanks should be encased in concrete.

7. A firm foundation is necessary, and the surrounding soft earth or sand should be well tamped. In preparing a tank excavation, it is suggested that 5 or 6 in. of sand be placed and tamped in the bottom of the hole upon which the tank can rest.

8. All buried tanks, prior to being placed underground, should be given a protective coating equivalent to hot-dip galvanizing or to two preliminary coatings of red lead, followed by a heavy coating of coal tar or asphalt. Before a tank is lowered into the excavation, it should be carefully examined to make sure there are no spots where this protective coating has been damaged. A bare spot will invite corrosion, and in a comparatively short time leakage will develop. Bare spots should therefore be cleaned and repainted. The container should be lowered so as to prevent abrasion or other damage to the coating. After the tank is lowered, the filling should first be of soft earth containing no hard earth, pebbles, or rocks that might injure the coating.

9. If the job of placing the tank is not completed in one operation, the excavation should be guarded by substantial barriers. Furthermore, such excavations should be posted with suitable warning signs, and they should be illuminated at night.

**Table 9-45. Permissible Location of Liquefied Petroleum Gas Storage Tanks<sup>1</sup>**

Water capacity per container, gal	Min distance, ft		Distance between above-ground containers, ft
	Under-ground	Above-ground	
Less than 125...	10	None	None
125-500 .....	10	10	3
501-1,200 ...	25	25	3
Over 1,200	50	50	5

NOTES: In cases of bulk storage in heavily populated or congested areas, the inspection department having jurisdiction shall determine individual restrictions.

In the case of buildings devoted exclusively to gas manufacturing and distributing operations, the above distances may be reduced, provided that in no case shall containers of capacity exceeding 500 gal be located closer than 10 ft to such buildings.

Any container used in domestic or commercial service, where transfer of liquid is made from such containers to portable containers, shall be located not less than 50 ft from the nearest building.

Readily ignitable material such as weeds and long grass shall be removed within 10 ft of any container.

<sup>1</sup> *National Board of Fire Underwriters Pamphlet 58*, p. 5, 1947.

10. Before underground tanks are installed, a check should be made to see that fittings are tight and suitably protected against damage. If fittings cannot be protected, extra care should be taken in lowering tanks.

11. Tanks buried underground should be placed so that their tops are below the established frost line, but in no case less than 2 ft below the surface of the ground. When necessary to prevent floating where high ground-water levels occur, tanks should be securely anchored or weighted.

12. Both aboveground and buried tanks should be fitted with spring-loaded safety-relief valves, and these valves should be arranged to afford free vent to the outside atmosphere with the point of discharge not less than 5 ft horizontally away from any openings into buildings which are below such discharge.

13. Liquid-level gauging devices should be provided on all tanks. Such devices, other fittings, and piping should meet the requirements of the latest revision of *National Board of Fire Underwriters Pamphlet 58* or that of the governing authorities having jurisdiction.

#### **Domestic Piping**

1. The systems for domestic service are of two general types, one in which the fuel enters the building as a gas, and one in which it enters as a liquid. In the latter system, the liquid is vaporized in a special vaporizer or in the burner itself by means of a preheater section. Such systems are considered more hazardous than systems in which only gas enters the building.

2. In domestic installation, no liquid or gas should enter buildings at more than 20 psi. Containers and first-stage regulating equipment should be located outside buildings other than those specially provided for the purpose.

3. Piping, fittings, and valves should be of a type approved for use with liquefied petroleum gases. Wrought iron, steel, brass, or copper pipe or seamless copper, brass, or other approved nonferrous gas tubing can be used. (Aluminum tubing is prohibited by *National Board of Fire Underwriters Pamphlet 58* in exterior locations or where it passes through masonry or plaster walls or insulation.) All piping should be suitable for a working pressure of not less than 125 psi. Piping and fittings should be extra heavy up to the first pressure-reducing valves so as to withstand the pressure in the tank.

4. All screwed valves, fittings, or other connections should be sealed against leakage by a pipe-joint compound that will provide a pure nonmetallic film. The compound should provide protection against corrosion or deterioration, making a perfect seal, not taking a permanent set; make it possible to remove valves or fittings at any time without damage; not be soluble in water, oil, or liquefied petroleum gas; and withstand a pressure of 250 psi. Ordinary pipe dope should not be used. Joints on gas tubing should be made by means of approved gas-tube fittings.

5. All systems should be tested and listed by *Underwriters' Laboratories*. All systems should be checked by competent installation men and should be inspected and approved by enforcing authorities (if any) having jurisdiction before they are placed in service.

#### **Safety in Handling**

"Handbook of Butane-Propane Gases" lists the following properties of liquefied petroleum-gases as ones which should be understood for the purpose of promoting safety in usage and for intelligent action in handling this fuel:

1. The gas or vapor is heavier than air.

2. The vapor or gas will diffuse into the atmosphere very slowly unless the wind velocity is high.

3. Open flames will ignite air-gas mixtures which are within the lower and upper inflammable limits.

4. Gas-air mixtures may be brought below the inflammable limit by mixing with large volumes of inert gases such as nitrogen, carbon dioxide, or steam.
5. Fine water sprays reduce the possibilities of igniting gas-air mixtures.
6. The vapor pressure of this fuel is greater than that of gasoline. It is safely stored only in closed pressure vessels built according to regulations and equipped with safety devices as required.
7. Liquids in open vessels will evaporate to form combustible mixtures with air even if the atmospheric temperature is many degrees below the boiling point.
8. The rapid removal of vapor from the tank will lower the liquid temperature and reduce the tank pressure. The rapid removal of liquid will not reduce the tank pressure.
9. The liquids will expand in the storage tank when atmospheric temperature rises. Storage tanks must never be filled completely with liquid. Refer to regulations showing outage required or filling density of storage tanks.
10. Liquid obtained from storage tanks will freeze the hands on contact, even if gloves are worn. This is due to the rapid absorption of heat by the liquid on vaporization in the open.
11. Condensation will occur in gas-distribution lines when surrounding temperatures are below the boiling point of the liquid.
12. The liquefied petroleum gases are excellent solvents of petroleum products and rubber products. Special pipe-joint compound and rubber substitutes are available for use in distribution systems.

#### **Further References on Storing and Using Liquefied Petroleum Fuels**

The National Board of Fire Underwriters and the National Fire Protection Association have jointly endorsed regulations and good-practice requirements dealing with the storage of liquefied petroleum gas and the installation of liquefied petroleum systems. These include: "Regulations for the Design, Installation, and Construction of Containers and Pertinent Equipment for the Storage and Handling of Liquefied Petroleum Gases," "Regulations Covering the Installation of Compressed Gas Systems Other Than Acetylene for Lighting and Heating," "Requirements for the Construction and Protection of Tank Trucks and Tank Trailers for the Transportation of Liquefied Petroleum Gases," and "Code Covering the Construction and Installation of Liquefied Petroleum Gas Systems Intended for Enforcement by Fire Marshals and Other Public Safety Agencies." (These codes and regulations are available through the National Fire Protection Association, Boston, Mass.)

Also the Accident Prevention Division of the Association of Casualty and Surety Executives, New York, has published an excellent series of pamphlets on the safety phases of liquefied petroleum gas. These include: "Liquefied Petroleum Gas—What It Is—How It Acts," "Safe Operation of Motor Vehicles Transporting Liquefied Petroleum Gases," "Safe Motor Vehicles and Equipment for Transporting Liquefied Petroleum Gases," "Safe Use of Liquefied Petroleum Gas as Fuel for Automotive Vehicles," "Safe Design and Operation of Central Plants for Liquefied Petroleum Gas Utility Service," "Safe Use of Liquefied Petroleum Gas in Industry," "Safe Use of Liquefied Petroleum Gas in Domestic Installations," and "Safe Storage, Transfer, and Distribution of Liquefied Petroleum Gas."

### **RETORT COAL GAS**

**Types of Equipment.**<sup>1</sup> Where gas rather than coke is the primary product desired, as in municipal gas plants, one of several types of coal-gas retorts is frequently used.

In the early days of the gas industry, small **D-shaped horizontal retorts** (capable

<sup>1</sup> HASLAM, ROBERT T. and ROBERT P. RUSSELL, "Fuels and Their Combustion," p. 685, McGraw-Hill Book Company, Inc., New York, 1925.

of taking a charge of 400 to 500 lb) stopped at one end were widely used. These retorts were inefficient, had high operating charges, and were subject to excessive naphthalene deposits.

Newer, larger, through types of **D-shaped retorts**, both **horizontal** and **inclined**, are subject to the same disadvantages, though to a lesser degree. They are retained mainly in small plants because of low first cost and flexibility.

The **vertical retort** was the next step in the evolution. These retorts, either intermittent or continuous in operation, permit automatic coal feed and gravity discharge of the finished coke. They can compete with the by-product coke oven in thermal efficiency and recovery of by-products. The fact that the coke produced cannot be used for metallurgical purposes is offset by the greater flexibility of the retort. The thermal yield of the gas is greatly increased by passing steam through the incandescent coke. In **continuous vertical retorts**, the constant movement of the coke through the retort is apt to result in a preponderance of small sizes.

**Types of Gas Produced.**<sup>1</sup> As is shown in Table 9-46, the types of gas produced in the different coal-gas retorts differ but slightly except that the gas from vertical retorts generally has a lower heating value, a higher percentage of hydrogen, and, possibly, a higher percentage of carbon monoxide because of the practice of steaming

Table 9-46. Typical Analyses of Retort Coal Gas<sup>1</sup>

Type of retort	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CO	H <sub>2</sub>	CH <sub>4</sub>	C <sub>4</sub> H <sub>10</sub>	Sp gr	Btu/cu ft	
									Gross	Net
Horizontal	2.4	0.8	11.3	7.4	48.0	27.1	3.0	0.47	542	486
Inclined	1.7	0.8	8.1	7.3	49.5	29.2	3.4	0.47	599	540
Continuous vertical	3.0	0.2	4.4	10.9	54.5	24.2	2.8	0.41	532	477
Intermittent, vertical	1.7	0.5	8.2	6.9	49.7	29.9	3.1	0.42	540	482
Intermittent vertical chamber	2.1	0.4	4.4	13.5	51.9	24.3	3.4	0.40	520	466

<sup>1</sup> SHENIDMAN, L., Editor, "Gaseous Fuels," p. 32, AGA, New York, 1948.

Table 9-47. Typical Horizontal Coal-gas-retort Operation<sup>1</sup>

	Yield per ton of coal charged (14,140 Btu/lb)	Yield, per cent by weight of coal	Heating value in products	
			Per cent of coal, Btu	Per cent total Btu in fuel used
Coal gas (saturated at 60°F)	12,000 cu ft (540 Btu/cu ft)	21.10	22.90	20.56
Tar (16,000 Btu/lb)	11.3 gal (113 lb)	5.65	6.39	5.74
Ammonia	5.0 lb	0.25	0.20	0.17
Coke (dry)	1,370 lb (12,950 Btu/lb)	68.00	62.73	65.30
Losses (by difference)		5.00	7.78	7.03
Total		100.00	100.00	89.80
Coke used in producers for heating retorts	250 lb			10.20
Net coke, including breeze	1,120 lb	55.0	50.4	

NOTE: These results are probably better than those obtained in small plants. Producer fuel may be 800 lb per ton of coal carbonized, and the tar and gas yields may be 10 to 20 per cent less than shown.

<sup>1</sup> SHENIDMAN, L., Editor, "Gaseous Fuels," p. 43, AGA, New York, 1948.

<sup>1</sup> SHENIDMAN, L., Editor, "Gaseous Fuels," p. 43, AGA, New York, 1945.

the retorts. Vertical retorts yield more tar and ammonia when the amount of steaming is increased. The analyses shown in Table 9-46 are those of the finished gases as served to the customer; actually, as the gas comes from the retorts, it contains other components which are removed before distribution.

Typical results for a coal-gas plant operating horizontal retorts using a waste-heat boiler and making more than 2 million cu ft of gas daily are presented in Table 9-47. Light oil was not recovered separately.

### BLAST-FURNACE GAS

One by-product from the operation of a blast furnace used in the manufacture of pig iron is called blast-furnace gas. It is derived from the partial combustion of coke. Because of the high temperatures needed for making iron, the gas contains 27 per cent carbon monoxide and over 70 per cent of inerts, giving it the lowest heating value of any of the commercially used gases. It has certain applications such as the operation of gas engines, heating by-product coke ovens, as well as for crude heating, for steel-plant heating and steam raising. Table 9-48 shows typical analyses of this gas.

Table 9-48. Typical Analyses of Blast-Furnace Gases<sup>1</sup>

Constituents, per cent by volume:						
Carbon dioxide . . . . .	14.5	13.0	15.6	8.7	5.7	6.0
Carbon monoxide . . . . .	25.0	26.2	23.4	32.8	34.0	27.0
Nitrogen . . . . .	57.5	57.6	59.3	56.5	59.0	60.0
Hydrogen . . . . .	3.0	3.2	1.7	1.8	1.3	2.0
Methane . . . . .	..	..	0.1	0.2	..	5.0
Density, lb/cu ft . . . . .	0.0775	0.0768	0.0788	0.0759	0.0749	0.0731
Btu/cu ft:						
Higher . . . . .	88	93	80	111	111	141
Lower . . . . .	87	91	79	110	111	135
Btu/lb:						
Higher . . . . .	1,140	1,208	1,012	1,463	1,487	1,932
Lower . . . . .	1,122	1,188	1,002	1,449	1,478	1,850
Atmospheric air at zero excess air (lb/10 <sup>6</sup> Btu)	574	574	565	577	573	627
CO <sub>2</sub> at zero excess air, per cent . . . . .	26.4	25.7	26.9	25.3	24.0	20.0

<sup>1</sup> "Combustion Engineering," p. 25-12, Combustion Engineering-Superheater Corp., New York, 1947.

### SEWAGE GASES<sup>1</sup>

Sewage sludges can be digested in appropriate equipment to produce a sewage gas averaging about 600 to 700 Btu per cubic foot. The general composition of sewage

Table 9-49. Composition of Typical Sewage Gases

City	CO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>	Btu/cu ft
Chicago, Ill. . . . .	14.7	0.5	..	76.6	8.2	775
Decatur, Ill. . . . .	22.0	..	2	68.0	6	690
Grand Rapids, Mich. . . . .	33.5	..	..	65.4	1.1	660
Rochester, N.Y. . . . .	30.0	0.0	0.0	66.0	4.0	670
Toronto, Ontario . . . . .	28.0	1.8	3.7	58.5	8.0	690
Stuttgart, Germany . . . . .	14.0	0	4.7	75.5	4.7	770
Birmingham, England . . . . .	30.0	0.0	0.0	67.0	3.0	680

<sup>1</sup> SHENIDMAN, L., Editor, *loc. cit.*, p. 46.

gas is about two-thirds methane ( $\text{CH}_4$ ) and one-third carbon dioxide ( $\text{CO}_2$ ), but a more complete analysis is given in Table 9-49.

The amount of this gas produced in typical sewage-digesting equipment varies from 0.3 to 1.0 cu ft per capita of population per day. The gas, by reason of its high inert content, has a slow rate of flame propagation. It will contain approximately 0.1 per cent of hydrogen sulphide ( $\text{H}_2\text{S}$ ) by volume, but this figure may run higher with consequent increase in the difficulty of using the sewage gas in gas engines or under boilers.<sup>1</sup>

### SYNTHESIS GAS<sup>2</sup>

The large-scale industrial utilization of chemical synthesis processes imposed on gas manufacturers, for the first time, the requirements of producing gases of a certain composition suitable for the synthesis.<sup>2</sup> The hydrogenation of solid and liquid fuels by the Bergius process for the purpose of synthesizing gasoline and lubricating oils, and also the synthesis of ammonia, required a high per cent of hydrogen in the gas; on the other hand, the Fischer-Tropsch process needs a carbon monoxide-hydrogen ratio in the very definite proportions of  $\text{CO}:\text{H}_2 = 1:2$ . The latter ratio is commonly considered a standard for synthesis gas, although, as has been shown, this requirement may vary with the process involved.

Usually, the production of gases high in hydrogen starts with the familiar water-gas process, which, in addition to the disadvantage of intermittent working and the unavoidable use of high-grade fuel, has the further drawback that it yields a gas containing too high a proportion of carbon monoxide. This gas, in which the  $\text{CO}:\text{H}_2$  ratio amounts to almost 1:1, must thus be converted, as with the addition of steam. The carbon monoxide and the steam react to form hydrogen and carbon dioxide, the latter being removed. By regulating the amount of carbon monoxide reacting, it is possible to obtain a synthesis gas of the desired composition.

Pressure gasification enables the formation of carbon monoxide to be restricted from two angles—through the gasification temperature and the pressure.

Practical tests for the production of a carbon monoxide-hydrogen gas mixture, suitable for the Fischer synthesis, showed that the gasification of low-temperature coal coke under a positive gasification pressure of 121 psi with a gasification medium of oxygen and steam yields a crude gas as shown in Table 9-50. In this gas the carbon monoxide and hydrogen are in the proportion of 1:2 desired for the synthesis. The sum of  $\text{CO} + \text{H}_2$  amounts to about 92 per cent of the gas mixture. According to earlier views, the methane is a disturbing factor, but later investigations into its influence in the benzene synthesis have shown that the presence of methane does not impair the reaction.

Proceeding still further, the formation of carbon monoxide may be reduced so extensively, by an increased addition of steam, that a pure gas containing 70 to 75 per cent of hydrogen and only 15 per cent of carbon monoxide is produced. This gas is excellently suited for the synthesis of ammonia and for hydrogenation.

In the production of synthesis gas, the advantages of pressure make themselves felt in the purification and cooling of the gas. In the scrubbing with water under pressure, in particular, the hydrogen sulphide is removed together with carbon dioxide, to such an extent as to obtain the purity of town gas. Tests also show that the

<sup>1</sup> Further details on sewage gas can be found in METCALF, LEONARD, and HARRISON P. EDDY, "American Sewerage Practice," Vol. III, McGraw-Hill Book Company, Inc., New York, 1935. On the use of sewage gas, refer to W. H. FULWEILER, *Sewage Works J.*, vol. II, p. 444, 1930. Articles on the use of sewage gas in engines include *Power*, vol. 120, 1936; *Eng. News-Record*, vol. 108, p. 283, Feb. 25, 1932; vol. 113, p. 626, Nov. 15, 1934.

<sup>2</sup> See section in Chap. 8 on Synthetic Fuels for methods of manufacture.

removal of organic sulphur, to attain synthesis purity, may also be substantially simplified by the employment of pressure.<sup>1</sup>

**Table 9-50. Analysis of Synthesis Gas<sup>1</sup>**

	Crude gas	Pure gas <sup>a</sup>
Constituents, per cent:		
Carbon dioxide . . . . .	29.3	1 0
Carbon monoxide . . . . .	21 9	30 7
Hydrogen . . . . .	44 0	61 6
Methane . . . . .	3.3	4.6
Nitrogen . . . . .	1 5	2.1
Co: H <sub>2</sub> ratio . . . . .	1:2 01	1:2.01
CO + H <sub>2</sub> amount, per cent.	65 9	92 3

<sup>1</sup> DANULAT, DR. ING. FRIEDRICH, "The Pressure Gasification of Solid Fuels with Oxygen," Lurgi Gesellschaft für Wärmetechnik. m.b.H., Frankfurt-am-Main.

<sup>a</sup> After removal of carbon dioxide by scrubbing with water under pressure.

### Methods of Manufacturing Synthesis Gas from Coal<sup>2</sup>

In the gas-synthesis process, the purified synthesis gas accounts for about 70 per cent of the cost of the finished product; in the hydrogenation process the cost of the compressed hydrogen represents one-half to one-third of the total cost of the product. Coal gasification to produce synthesis gas or hydrogen is thus one of the most important problems in converting coals to synthetic liquid fuels.

To date, all synthesis gas produced commercially in this country has been obtained by gasifying by-product coke in standard water-gas machines. There are several objections to continuing this practice for the production of synthetic liquid fuels:

1. Coking coals in enormous quantities would be required for a large synthetic-fuel industry, and such relatively scarce coals should be conserved for the manufacture of metallurgical coke or other preferred uses.

2. Noncoking coals form a large part of the country's coal reserves.

3. A substantial reduction in costs appears to be possible by directly gasifying coal rather than by first coking it and then gasifying the coke.

Although virtually all the suggested processes for directly gasifying coal are in the experimental stage, the following are attracting the most research attention:

1. **Gasification of powdered coal** in an atmosphere of oxygen and steam. This process is expected to be the one most independent of coal characteristics.

2. **Gasification in a fluidized bed** in an atmosphere of steam and oxygen.

3. **Gasification in an externally heated retort** (Parry process, see Synthetic Fuels section in Chap. 8 for further description).

4. **Lurgi pressure gasification**, requiring a reactive, noncoking, sized fuel (see section on Synthetic Fuels).

5. **Fixed-bed process** such as experiments at Battelle Memorial Institute, Columbus, Ohio.

6. **Underground gasification**, as at Gorgas, Ala. (U.S. Bureau of Mines and Alabama Power & Light Co.).

<sup>1</sup> DANULAT, DR. ING. FRIEDRICH, "The Pressure Gasification of Solid Fuels with Oxygen," Lurgi Gesellschaft für Wärmetechnik. m.b.H., Frankfurt am Main.

<sup>2</sup> DOHERTY, J. D., AIME-ASME Joint Fuels Conference Technical Paper, White Sulphur Springs, November, 1948, as published in *Trans. AIME*, April, 1949, pp. 116-124.



7. **Low-temperature Carbonization** (see Synthetic Fuels section). Frequently mentioned as a source of synthesis gas and giving the following typical yield:

	<i>Yield</i>
Coke, lb . . . . .	1,400-1,600
Gas (Btu 800 to 1,000), cu ft . . .	3,000-5,000
Tar, gal . . . . .	20-30
Light oil for motor fuels, gal. . . .	2 5-3 0

While a combination with synthesis plants is possible, the Bureau of Mines believes the direct gasification of bituminous coal to have advantages of lower costs and wider application to the different coals available.

### MIXED GASES

Physically, all the gases in this section may be mixed in any proportions without causing any chemical interaction between components. However, the factors which limit the extent to which any given combination of gases can be mixed without causing difficulty in gas-appliance operation are both varied and complex. The AGA has made an extensive study of this matter and discusses the several factors in detail in Chap. VIII of "Gaseous Fuels." As this is too involved for handbook treatment, reference is made to that work for the effect of mixing gases.

## CHAPTER 10

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### MISCELLANEOUS SOURCES OF HEAT AND POWER

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## ELECTRIC HEATING

### Electric Resistance Heating<sup>1</sup>

Resistance heating has been applied to describe the method of passing electric current through a resistance material and transforming this heat by means of conduction, convection, and radiation.

**Advantages** include inherent efficiency of virtually 100 per cent in converting electric power into heat energy, high thermal efficiency in transferring this heat to the work, ready adaptability to standard power circuits, moderate investment cost, and reliable service.

**Disadvantages** include limitations to temperatures well below those required for some purposes; limitations in density of heat input where great concentration of heat energy is required; and its inability to heat uniformly some materials, such as dielectrics, except by slow conduction through their mass.

**Resistance heating elements** are made in various sizes and shapes according to use. The most popular are exposed resistors of nickel-chromium wire or ribbon, resistors embedded in compressed refractory powder within metal sheath enclosures, and heavy-duty wire or ribbon supported by preformed refractory insulators. Exposed resistors deliver heat by either convection or radiation; sheathed resistors depend largely upon conduction.

**Factors of Design.** The more important factors of design include the required maximum kilowatts per hour, the maximum permissible temperature for the heated surfaces in contact with the work being heated, the total area of the heated surface needed to allow the required energy input without exceeding the permissible maximum temperature, the watt density necessary to deliver the required energy input, corrosion, time factor, insulation, controls, and the maximum safe temperatures of the heating elements.

**Watt Density.** The selection of a proper watt density is of prime importance. Each material being heated has its own critical temperature and its own maximum rate of satisfactory heat absorption. These factors govern the selection of the permissible surface temperature in contact with the work. The permissible watt density depends on the capacity of the work material to absorb heat. For instance, molasses cannot be heated with so high a watt density as water, and even water varies according to its content of lime or other substances. Values of watt densities frequently used in practice are given in Table 10-1 with the caution that they are valid only when used in conjunction with correct over-all design. As isolated values, they are worthless.

**Temperature of Heating Element.** The temperature of a heating element depends on the watt density per unit of surface; the maximum heat gradient between the element and the work; and the maximum ambient temperature of the work. **It is of utmost importance to remember that, unlike steam heating, operating temperature of an electric heater is not a fixed value but varies with ambient temperature changes.** Maximum safe temperatures are shown in Table 10-2. The heat density rating and safe operating temperatures of electric heaters must be designed for maximum temperature when operating at maximum ambient temperature.

**Constant Input.** With electric heating, the energy input is practically constant and temperatures rise at a nearly uniform rate because the heat gradient remains substantially constant. For example, unlike steam coils, no change in electric-

<sup>1</sup> HYNES, LEE P., Industrial Electric Resistance Heating, *Trans. AIEE*, vol. 67, 1948.

Table 10-1. Typical Watt Densities of Electric Resistance Heaters<sup>1</sup>

Type of service	Watts/ sq in. of surface	Remarks
Furnaces: nickel-chromium exposed resistors Furnaces: carbon or graphite resistors in an inert atmosphere . . . . . Radiation heaters: nickel-chrome resistors .	10- 20 80-120 25- 40	Depends on operating temperatures
High-velocity industrial air heaters. Fan circulation unit air heaters and duct heaters . . .	15- 30 15- 20	Depends on air velocity and temperature
Water heaters . . . Steam boilers . . . . .	29- 45 10- 20	Depends on water analysis and temperature
Dowtherm boilers . . . . .	7- 12	Depends on liquid temperature
Circulating oils, 100-200°F . . . . . Circulating oils, 250-600°F . . . . .	9- 12 6- 9	Depends on type of oil, velocity, temperature, and flow design
Convection heating, pitch, and compounds .	1- 3	Depends on material, temperature, and design details

<sup>1</sup> HYNES, LEE P., "Industrial Electric Resistance Heating," AIEE Middle Western general meeting, Milwaukee, October, 1948.

Table 10-2. Maximum Safe Temperatures for Electric Heating Elements<sup>1</sup>

	Deg F
Carbon-graphite resistors surrounded by an inert atmosphere . . . . .	3000 <sup>a</sup>
Nickel-chromium exposed resistors . . . . .	2100
Nickel-chromium resistors, sheathed in special alloys . . . . .	1500 <sup>b</sup>
Nickel-chromium resistors, sheathed in plain steel . . . . .	750

<sup>1</sup> HYNES, LEE P., Industrial Electric Resistance Heating, *Trans. AIEE*, vol 67, 1948.

<sup>a</sup> Lower temperatures result in longer life.

<sup>b</sup> Or as specified by the manufacturers.

Table 10-3. Characteristics and Uses of Resistor Materials<sup>1</sup>

Material	Composition	Characteristics	Uses
Advance.	Cu 55%, Ni 45%	Low temperature coefficient; high thermoelectric power to copper; noncorrosive	Measuring instruments; precision equipment; thermoelements; pyrometers; rheostats
Hytemco .	Ni 50%, Fe 50%	High temperature coefficient	Where self-regulation is required, as in immersion heaters and heater pads
Magno..	Ni 95.5%, Fe 4.5%	Magnesium-nickel alloy	Incandescent lamps and radio tubes
Manganin	Cu 84%, Mn 12%, Ni 4%	Very low temperature coefficient; low thermal emf with respect to copper	Very valuable for high-precision electrical measuring apparatus. Resistance units in bridges, shunts, multipliers, etc.
Nichrome V	Ni 80%,	Free from iron; noncorrosive; nonmagnetic; withstands high temperatures; high resistivity	Heating elements in electric furnaces, hot-water heaters, ranges, radiant heaters, and high-grade appliances
Pure nickel .	Ni 100%		Radio tubes; incandescent lamps; combustion boats; resistance thermometers
Carbon . . . . .	C	High resistance; withstands high temperatures; temperature coefficient negative; will safely carry 125 amp/sq in.	Carbon for rheostats, etc. Amorphous carbon has resistivity of 3,800-4,100 microhms/cc; retort carbon 720 microhms; graphite 812 microhms

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 2055, McGraw-Hill Book Company, Inc., New York, 1941.

Table 10-4. Properties of Metals, Alloys, and Resistor Materials<sup>1</sup>

Material	Composition	Sp gr	Microhms /cc at 20°C	Ohms/ cir mil ft at 20°C	Temp co- efficient of resistance	Temp range, deg F	Max safe work temp, deg F	Approx melting point, deg F
Advance...	Cu, Ni 0.45 %	8.9	49	294	0.00002	68-212	930	2210
Comet ...	Ni 0.30 %, Cr 0.05 %, Fe 0.65 %	8.15	95	570	0.00088	68-930	1110	2700
Bronze (commercial)	Cu, Sn	8.7	4.2	25	0.0020	32-212		1860
Hytemco. . .	Ni 0.50 %, Fe 0.50 %	8.46	20	120	0.0045	68-212	1110	2595
Magno.....	Ni 0.955 %, Mn 0.045 %	8.75	20	120	0.0036	68-212	750	2615
Manganin.....	Cu 0.84 %, Mn 0.12 %, Ni 0.04 %	8.19	48.2	290	0.000015	59-95	170	1870
Monel metal...	Ni 0.67 %, Cu 0.28 %	8.9	42.6	256	0.00198	68-212	800	2460
Nichrome.....	Ni 0.60 %, Fe 0.25 %, Cr 0.15 %	8.25	112	675	0.00017	68-212	1700	2460
Nichrome V..	Ni 0.80 %, Cr 0.20 %	8.41	108	650	0.00013	68-212	2010	2550
Nickel (pure)	Ni 0.99 %	8.9	10	60	0.0050	32-212	750	2640
Platinum...	Pt	21.45	10.6	63.8	0.00398			3190
Silver .....	Ag	10.5	1.6	9.755	0.00361			1760
Tungsten . .	W	19.3	5.5	33.22	0.00524			6000

<sup>1</sup> From Driver-Harris Co. as contained in MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 2054, McGraw-Hill Book Company, Inc., New York, 1941.

Table 10-5. Energy Consumption of Electric Furnaces<sup>1</sup>

Process	Type of furnace	Lb/kwhr
Baking finishes on sheet metal	Batch oven	10-18
Baking finishes on sheet metal.	Continuous oven	25-30
Baking bread . . . . .	Continuous oven	10-12
Annealing brass and copper..	Batch furnace	10-25
Annealing steel . . . . .	Batch furnace	5-15
Hardening steel . . . . .	Batch furnace	7-11
Tempering steel . . . . .	Batch furnace	15-25
Annealing glass . . . . .	Continuous furnace	40-100
Vitreous enameling, single coat ....	Batch furnace	5-8
Vitreous enameling, single coat	Continuous furnace	10-15
Galvanizing . . . . .	Batch furnace	12-20
Melting metals	Type of furnace	Kwhr/ton (2,000 lb)
Lead . . . . .	Resistor	40-50
Solder (50-50)	Resistor	40-50
Tin . . . . .	Resistor	35-50
Zinc . . . . .	Induction	80-100
Brass . . . . .	Arc and induction	250-400
Steel (melting only)	Arc and induction	450-700
Steel (melting and refining) ..	Arc	650-900
Gray iron . . . . .	Arc	500-700
Furnace products	Type of furnace	Kwhr/ton (2,000 lb)
Aluminum . . . . .	Electrolytic	22,000-27,000
Calcium carbide . . . . .	Resistance	3,000-6,000
Ferroalloys . . . . .	Resistance	4,000-8,000
Graphite. . . . .	Resistance	3,000-8,000
Silicon carbide . . . . .	Resistance	8,500-10,000
Smelting iron ore . . . . .	Resistance	2,100-2,400

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 879, McGraw-Hill Book Company, Inc., New York, 1941.

energy input will result from reducing the air flow over an electric element, because reduced air flow will merely result in a corresponding rise in the temperature of the air (or other medium) that does pass over it.

**Applications of Resistance Heaters.** For temperatures up to 600°F, hot oil can be recirculated by a suitable pump through an electric oil heater and a jacketed vessel or work kettle at pressures usually not over 20 psi. Systems of this type are commonly used up to about 300 kw capacity.

Dowtherm is also a useful heat-transfer medium whereby vapor can be utilized at high temperature at far lower pressure than steam at equal temperature. As an example, Dowtherm A vapor has a pressure of only 88 psi at 700°F.

The surface heating of materials by infrared heat, superheating of steam under very close temperature control, direct heating of air and gases, and immersion heating of liquids are but isolated examples of the many applications of electric resistance heating.

### Electric Induction Hardening<sup>1</sup>

**Definition of Induction Heating.** Simply stated, induction heating is the heating of a nominally conducting material due to its own  $I^2R$  losses when the material is placed in an electromagnetic field. Thus, if a steel rod is placed in an inductor coil which carries an alternating current, the varying magnetic field caused by the ampere-turns of the coil couples the steel rod and induces a voltage which, in turn, causes a circulating current, in the same way that it would induce a current in a closed loop of copper wire. Once the bar is properly positioned in the inductor, the depth to which the heat penetrates in the rod is a function of the physical characteristics of the steel, *i.e.*, the metallurgy of the steel, the frequency of the current, and the power used.

**Metallurgical Considerations in Hardening.** Fundamentally, to obtain an acceptable hardness in a steel bar, the material must be heated to a temperature above its upper critical point and quenched within a limited time in order to convert the austenitic solution into a final structure known as martensite.

**Depth of Hardness.** When a bar is inductively heated, the surface tends to reach the critical temperature first and, if the heating cycle is short, as is the case of hardening, the temperature in each succeeding layer drops very fast to the point where the core may still be at room temperature.

The hardened depth, commonly referred to in induction heating, is considered to be the depth below the surface where the hardness, as indicated by a Rockwell tester, has decreased to 50 Rockwell, C dial, or approximately 50 per cent martensite. The metallurgically correct structure for maximum hardness is approximately 100 per cent martensite.

**Importance of Time in Induction Hardening.** It is important to note that the transition into the austenitic solution does not take place immediately but is a function of time as well as the prior structure of the steel. In general, the prior structure of steel can be grouped into four classifications: annealed, spheroidized, normalized, and quenched and drawn or heat-treated. The annealed state, containing a mixture of pearlite and ferrite, takes the longest time to go into austenitic solution; and the heat-treated state, consisting of fine sorbitic structure, takes the shortest time. In fact, when heating the annealed or spheroidized specimens, it is often necessary to increase the temperature and time to obtain the solid solutions. As examples of the time required for induction hardening, crankshafts varying in diameter from  $\frac{3}{4}$  to  $2\frac{3}{8}$  in. are hardened in from  $1\frac{1}{2}$  to  $5\frac{1}{2}$  sec. This is quite in contrast to other methods of heating.

<sup>1</sup> TÊMIN, J. T., "Designing for High Frequency Induction Hardening," ASME Paper 48-SA-32, Milwaukee semiannual meeting, 1948.

If two specimens of different heat-treatment were to be heated and quenched for the same period of time, the result would be a difference in the hardened depth.

Of more importance is the now apparent fact that, since there is a rapid transition into the austenitic state with a resulting increase in hardening depth, the heating time can be decreased and the specimen quenched faster to obtain a shallower hardness depth than is otherwise possible.

**Power vs. Hardened Depth.** The effect of hardened depth due to increasing the energy input to work parts is important. Generally speaking, increasing the energy increases the hardness depth. However, as before, the function of time cannot be disregarded, for increasing time beyond certain critical limits may result in surface overheating, causing grain growth and resulting in a decrease in surface hardness.

**Frequency Considerations.** Because of the phenomenon of skin effect, the induced current tends to hug the surface. The higher the frequency, the less depth heated, and the shallower the depth hardness.

**General Advantages.** One of the outstanding features of induction hardening is the tendency to minimize distortion, especially where a long bar is to be surface hardened. Distortion can be further minimized by rotating the part during the heating and quenching operation. If, however, the surface to be hardened contains an obstruction or irregular surface, rotation may have to be eliminated because of the uncontrolled splashing during quenching.

**References for Design Data.** The proper application of electric induction hardening combines the subjects of metallurgical, electrical, heat, and production engineering. Every problem is one of different metal characteristics, part shapes, and production required. In addition, there are several distinct processes, suited to specific problems. It is thus not feasible to attempt to summarize design data, but is preferable to refer to a manufacturer of induction equipment, such as Ohio Crankshaft Co. (Cleveland), Induction Heating Co. (Brooklyn), and Westinghouse (Pittsburgh).

### Conductive Rubber Panel Heating (Uskon)

Uskon electric heating panels, as manufactured by the U.S. Rubber Co., contain a conductive rubber heating element sandwiched between insulating layers of phenolic-impregnated paper with the assembly backed by a  $\frac{3}{16}$ -in. asbestos board. No wires are used within the panel other than the two connecting leads; the rubber itself conducts the electricity.

The panels are manufactured in *two wattages*, 17 watts per sq ft (55 Btu per sq ft) and 22 watts per sq ft (75 Btu per sq ft). Both are operated on 220 volts. The panels are approximately  $\frac{1}{4}$  in. thick and are manufactured in 3- by 4-ft, 4- by 4-ft, and 4- by 8-ft sizes. Surface temperature achieved by the 17 watt per sq ft panel on a design day approximates 100°F with on-off control, 120°F with continuous operation.

Recommended percentage covering of the ceiling by active paneling follows:

Average Per Cent Coverage	Design Temp
70	- 15°F and lower
65	- 10°F
60	- 5°F
60	0°F
55	+ 5°F and higher

Such figures are useful for preliminary estimates only and should be modified when heat-loss estimates are available.

According to the manufacturers, the approximate annual kilowatt-hour electric consumption is

$$\frac{0.3 \times \text{cubic footage of house} \times \text{degree days}}{1,000}$$

**Notes on Installation.** Panels cannot be cut. As applied to existing installations, 2-in. furring strips are used, and 2 to 3½ in. of insulation should be used behind the panels. The house should be well constructed and insulated. Nails or screws must be carefully placed in the 1½-in. depressed margin at the edge of the panel only; nails cannot be driven in the center of the panel. Drilling or punching is required prior to fastening. Plaster cannot be used on the panel surfaces. Joints must thus be concealed by covering strips or filler material, the permanency of the latter not being guaranteed by the manufacturer.

### Electric Panel Heating with Aluminum Foil

Experimental installations have been made at the Purdue Research Foundation in which panel heating of heavily insulated (wall  $U'$  value 0.065) structures is achieved by means of applying thin strips of aluminum foil between a fiber wallboard 1 in. thick and the regular wallpaper and passing an electric current through the heating grid thus formed.

In a typical installation, 400 lin ft of 0.00065-in. aluminum foil 1 in. wide was applied in continuous grid form. The foil was paper-mounted for easy handling and was stapled to the wallboard. The foil resistance element was directly attached to a 110-volt line, drawing 20 amp with an output of about 7,500 Btu per hr. Two ceiling circuits of this size are employed per room to provide quick heating acceleration when needed.

With the ceiling alone being used as a panel, maximum temperatures are in the order of 140°F; this can be reduced to as low as 70°F if the walls are also provided with electric grids.

The author, Carl F. Boester, also describes making grids from sheets of foil-backed wallboard in which a 1½-in. strip circuit is cut out by a sharp knife. Using 4- by 8-ft board, a continuous grid draws about 13 amp (foil 0.00035 in. thick) and yields about 152 Btu per sq ft when mounted vertically. Multiples of such panels can be used to heat various sized spaces. Operating costs depend on electric rates, hours of use, insulation, and other factors.

### The Heat Pump<sup>1</sup>

Although frequently referred to incorrectly as the reverse-cycle system, the heat-pump cycle is identical with the ordinary refrigeration cycle and differs only in the sense that the desired effect is rejection of the heat from the condenser rather than absorption of the heat in the evaporator.

The economical application of the heat pump as a practical means of heating requires that the temperature of the source from which the heat is extracted be as high as possible and that the temperature of the sink to which the heat is rejected for heating purposes be as low as possible. Thus, with a small temperature spread between the evaporator and the condenser, six or more times as much heat may be obtained theoretically, and three to five times practically, as the heat equivalent of the work necessary to operate the system. This is much better performance than straight electric heating where the heat available for the building is exactly equal to the power consumed. The ratio of the useful heat received to the heat input of the system, as, for example, in electricity, is known as the "coefficient of performance," commonly called COP.

**Sources of Heat.** The heat pump will operate on any available source of heat, provided only that its temperature may be relied upon to be even only a few degrees higher than the temperature that can be discharged. This includes ground water

<sup>1</sup> From "Heating, Ventilating and Air Conditioning Guide," Chap. 39, p. 765, ASHVE, 1949. Used by permission.



such as lakes, streams, rivers, and surface wells; the atmosphere; or even the ground itself. Nevertheless, the most serious limitation in the application of the heat pump is the usual lack of ready availability of a practical, reliable, and adequate source of heat. A further listing of potential heat sources, with some of their inherent disadvantages follows:

1. Air may be used, but its specific heat is low and its temperature uncertain. When the most heat is needed, the temperature of the air is the lowest, thus resulting in the least favorable temperature combination. Practical considerations seem to limit the use of present air systems to climates such as those encountered in the southern United States or California, where temperatures under 20°F are not encountered and where the owner is willing to pay for summer cooling as well as heating.

2. Water from wells, lakes, and rivers may be used. Well water is the most desirable, since its temperature is fairly constant throughout the entire year. As water temperature is relatively high, even in winter, a large amount of heat may be removed relative to the weight of water handled. Means of returning the water to the under-

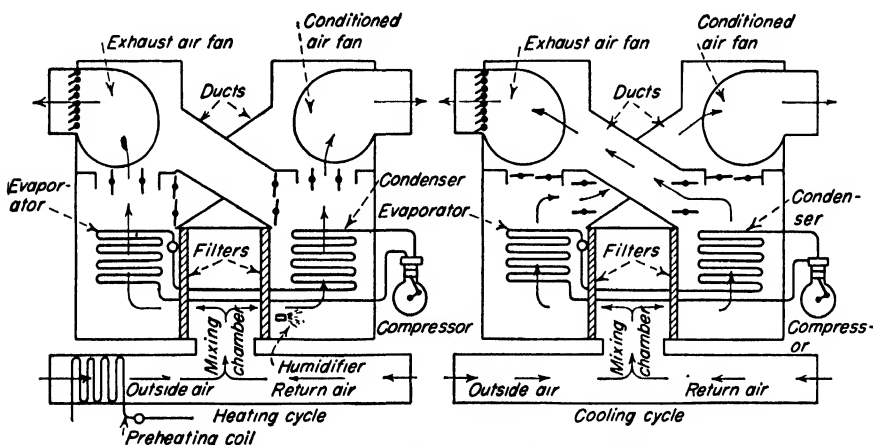


FIG. 10-1. Electric heat pump, heating and cooling cycle. (ASHVE Guide, 1949.)

ground reservoir should be provided to prevent depletion. The disadvantages of using water include the problem of locating an adequate supply, the cost of pumping, and the problem of water disposal.

3. The earth may be used as a source of heat with the refrigerant coils buried in the ground or with a heat exchanger supplied by a water-circulating coil buried in the ground. One disadvantage appears to be the large amount of heat-transfer surface required. Another is the apparent difficulty of estimating the amount of heat which can be obtained in a given locality. This is due in part to rather meager data on the subject and in part to the many variables of changing moisture content, freezing, differences between the actual transfer factor and the calculated conductivity, etc. Requisites for ground coils seem to be location in soil which allows a free movement of moisture, in areas with mild wet winters. For such soils with 20 to 30 per cent moisture, heat-transfer rates of 2 to 10 Btu/sq ft/hr/deg F are reported. Deviations between calculations and actual transfer in the work of competent engineers frequently amount to as much as 200 per cent, with the actual transfer rate usually being the greater (see Chap. 20 for underground heat conditions).

Since development of a heat pump to date includes the use of air, water, and earth as heat sources, and air and water as heat sinks, there are six possible combinations of

source and sink in application: air to air, air to water, water to air, water to water, earth to air, and earth to water.

**Coefficient of Performance (COP).** For domestic heat-pump installations, the average coefficient of performances as calculated by Penrod<sup>1</sup> for 7 installations is 3.58 (and as calculated for 15 commercial installations, 3.31). While there is a considerable variation in COP figures according to the heat source, application, etc., a low of 2.9 and a high of 3.75 may be considered as representative of the design range. Exceptions are noted where relatively hot heat sources are available (*e.g.*, a 66°F well-water installation in Buenos Aires with a reported COP of 5.45).

**Table 10-6. Comparison of Heat-pump Operating Costs with Other Fuels**

COP. . . . .	3.00	3.25	3.50	3.75	4.00
Fuel oil, cents/gal. . . . .	9.6	8.8	8.2	7.6	7.2
Anthracite, dollars/ton. . . . .	16.49	15.24	14.14	13.20	12.74
Bituminous, dollars/ton . . . . .	16.40	15.14	14.06	13.12	12.30
Mfg gas, cents/Mcf . . . . .	44.8	41.4	38.4	35.9	33.7
Natural gas, cents/Mcf . . . . .	82.3	76.6	71.1	66.9	62.3

Figures in body of table represent costs of stated units of competing fuels that would equal the cost of electricity at 1 cent per kilowatt-hour.

**Example.** (1) If electricity is 1 cent per kilowatt-hour and the COP is known or assumed to be 3.50, the operating cost of the heat pump would equal that of oil if the latter was 8.2 cents a gallon. (2) If oil was 10 cents a gallon in reality, the heat pump would save 10 - 8.2, or 1.8 cents on each gallon formerly used. (3) If electricity is other than 1 cent, it is necessary to multiply the figure in the table by the ratio to 1 cent; thus 2-cent electricity would equal  $2 \times 8.2$ , or 16.4, cent oil, and oil at 10 cents would then be 6.4 cents per gallon cheaper than the heat pump.

**Basis of Calculations.** Oil, 140,000 Btu per gal, 70 per cent efficiency; anthracite, 13,000 Btu per lb, 65 per cent efficiency; bituminous coal, 14,000 Btu per lb, 60 per cent efficiency; manufactured gas, 540 Btu per cu ft, 85 per cent efficiency; natural gas, 1,000 Btu per cu ft, 85 per cent efficiency.

**Economics of the Heat Pump.** Table 10-6 shows the cost at 1 cent per kilowatt-hour of the amount of electricity that would be required to replace stated unit quantities of various competing fuels. The unit price of 1 cent per kilowatt-hour was used only to avoid a duplication or complication of the table, it being intended that the figures found in the table be multiplied by the ratio of the actual price of local electricity to 1 cent for practical use (or, essentially, by the actual price itself).

This table shows that, with a COP of 3.50, 1-cent electricity is equal in operating cost to 8.2-cent oil or \$14.14 anthracite. The fuel cost is therefore competitive in many localities. Unfortunately, this is not the full story of heat-pump costs, since the original and installation costs are both very much higher than those of other heating systems. One of the most expensive phases in most instances is a provision of a proper source of heat and of heat return.

**Commercial Installations.** At present, commercial custom-built applications have the edge over domestic packaged units. The widely differing conditions in heat sources in different localities makes standardization difficult and stresses the need for very competent field engineering in each instance. Further, the higher internal heat gain from such sources as humans and machinery decreases the winter and increases the summer load in commercial installations to more nearly approach the highly desirable balance. In domestic use, the actual load factor is in the neighborhood of only 25 per cent, which would impose a tremendous burden on central stations if heat pumps were to become widespread. (Central-station equipment involves an investment of some \$400 per kilowatt-hour of installed capacity.) An idea of the cost of ground coils is gained from one manufacturer's recommendation of 135 to 235 ft of

<sup>1</sup> PENROD, E. B., A Review of Some Heat Pump Installations, *Mech. Eng.*, vol. 69, pp. 639-647, August, 1947.

tubing to cover an area of 1,100 to 1,500 sq ft (and buried at least 4 ft underground) for each horsepower capacity of the heat pump.

**Underground Water.** Figure 10-2 shows contours of probable underground water temperatures for the United States.<sup>1</sup> In planning to use such water, it is important to note that underground flow may be as low as 4 miles per year or even less. Thus, if the sink is too close either vertically or horizontally, or if there are too many heat pumps in such localities, a condition may be reached rapidly where the temperature of the ground water will be lowered to a point of materially decreased effectiveness. To date, little is known about the possible total heat-pump capacity of a neighborhood or community depending on ground water.

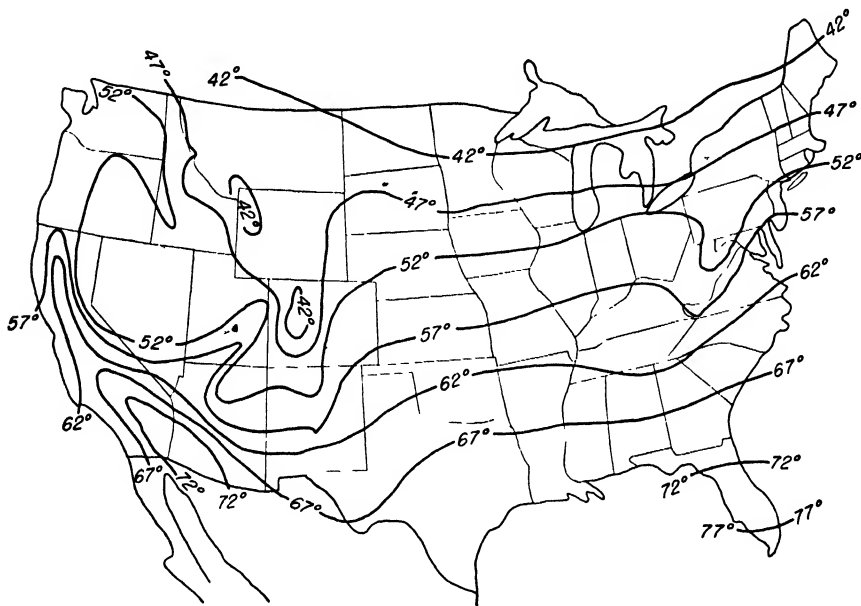


FIG. 10-2. Approximate water temperature from nonthermal wells 30 to 60 ft deep. (*Stringfield, Heating and Ventilating Magazine, June, 1945.*)

**Uses for Industrial Processing.** According to W. E. Johnson,<sup>2</sup> several industrial processes are ideal for the application of the heat pump, including the concentration of solutions such as milk, fruit juices, and sirup. This can be accomplished by any one of three methods: multistage evaporation, direct compression of vapor, and indirect compression. With a four-stage evaporation system, for example, he showed that 3 lb of steam can be evaporated for 1 lb of steam used with resultant important savings.<sup>3</sup>

**Typical Domestic Application.** Table 10-7 shows the operating results of a domestic heat-pump application as described by Wetherbee.<sup>4</sup> This installation is located in a one-story six-room dwelling of 1,433 sq ft floor plan, located 20 miles west of Chicago.

The heating system consists of a 5-hp compressing unit, a conventional duct system for air distribution, and a combination of earth-buried and atmospheric coils as a heat

<sup>1</sup> Additional data on underground temperatures will be found in Chap. 20, *Heat Transfer and Insulation*.

<sup>2</sup> Manager, Engineering Division, General Electric Co.

<sup>3</sup> ASHVE New York annual meeting, February, 1948.

<sup>4</sup> WETHERBEE, G. D., *Heating with the Heat Pump, Heating, Piping, Air Conditioning*, September, 1949, pp. 88-92.

source. The evaporator is made up of 1-in.-OD Freon-filled copper tubing, approximately 770 ft long (plus 148 ft of  $\frac{5}{8}$ -in. tubing), buried  $5\frac{1}{2}$  to 6 ft below the surface. The  $\frac{1}{2}$ -hp air conditioner contained a primary surface of 24.1 sq ft, finned surface of 363.5 sq ft, and total surface of 387.6 sq ft.

**Table 10-7. Typical Heat-pump Operating Data<sup>1</sup> (January–May, 1949)**

Volume of structure, cu ft.....	14,000
Degree days .....	3,878
Total electricity consumed, kwhr .....	5,582
Condensing unit, kwhr....	5,024
Fan, kwhr.....	372
Pump, kwhr.....	186
Hours of operation .....	1,064
Watts (4,700 + 350 + 400) .....	5,450
Heat of refrigeration at 40,400 Btu/hr, Btu .....	43,000,000
Electrical heat (three motors) .....	19,000,000
Hours of operation per degree day .....	0 289
Kwhr per degree day .....	1 52
Kwhr for 6,300 degree days (Chicago) .....	9,550
Kwhr per degree day per 1,000 cu ft .....	0.108
COP condition unit only. . .	3 52
COP three motors .....	3.26
Load factor, per cent. . .	28 3

<sup>1</sup> WETTERBEE, G. D., Heating with the Heat Pump, *Heating, Piping, Air Conditioning*, September, 1949, pp. 88–92.

## WATER POWER<sup>1</sup>

The earliest recorded use of power is that of crude water wheels revolving on vertical shafts connected directly to millstones. Such wheels were described by Vitruvius in 16 B.C. and by Hero of Alexandria about 100 years earlier. They were used almost exclusively for the grinding of wheat and other grains at that time, since power was seldom used for any other purpose for more than 1,000 years.

Water may do useful work in four general ways: (1) by its pressure, (2) by its velocity, (3) by its weight, and (4) by various combinations of these three. Of these, velocity and combination are employed most generally in impulse and reaction turbines, respectively. Overshot water wheels and breast wheels utilize weight; undershot and current wheels use velocity; and pressure motors use pressure except in the smaller sizes.

### Water Wheels

Water wheels, which have now been almost entirely displaced by the more modern turbines, may be divided into three general classes:

**1. Overshot wheels**, which receive their water at the top and are thus necessarily of a diameter less than the total head of water. Weidner<sup>2</sup> classes them as being suitable for waterfalls ranging from 10 to 70 ft, where the water supply is 2 to 30 fps. For maximum efficiency, the circumferential velocity of the water should be approximately 1.1 times the circumferential speed of the wheel. The point of impact of the water should be as high in the wheel as possible. The efficiency will be seriously decreased if the wheel is submerged in the tail water.

**2. Breast Wheels.** The water enters the wheel at the upstream side, either (type 1) flooding the buckets or (type 2) being directed against them in a stream making an angle of about 27 deg with a tangent to the circumference at the point of entry, and is prevented from leaving them by a breast wall just clearing the lower quadrant of the wheel on the entry side. In addition to the general dimensions shown in Table 10-8, the circumferential pitch of the buckets is  $0.5d$  to  $0.7d$  ( $d$  being depth of buckets).

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., pp. 1341–1343, McGraw-Hill Book Company, Inc., New York, 1941.

<sup>2</sup> WEIDNER, CARL D., "Theory and Test of an Overshot Water Wheel," *Bull. Univ. Wis.*, 529.

**3. Undershot Wheels.** Where the head does not exceed 6 ft, the Poncelet undershot wheel is probably the best type. The water jet, 8 to 10 in. in thickness, flows down a 1:10 slope, enters the wheel without shock, follows up the curved vanes or buckets, never, however, quite filling them, falls back, and leaves the wheel practically

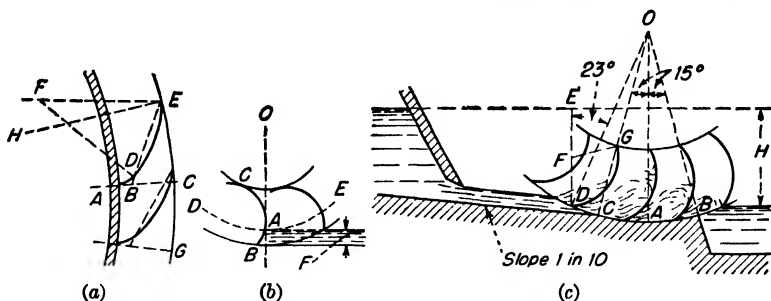


FIG. 10-3. Curvature of water-wheel buckets. (a) Over-shot wheel; (b) breast wheel; (c) undershot wheel.

without velocity. A close-fitting breast at the bottom should cover 15 deg each side of the vertical wheel diameter.

**Horsepower of water wheels** is  $0.1134QHE$ , where  $Q$  equals water available in cubic feet per second,  $H$  equals head, and  $E$  equals product of hydraulic and mechani-

Table 10-8. Critical Dimensions of Water Wheels<sup>1</sup>

	Overshot wheels	Breast wheels		Undershot wheels (Poncelet impulse)
		Type 1	Type 2	
Available head of water, $H$ , ft. . . . .	10 to 70 <sup>a</sup>	1.3 to 12	5 to 17	Up to 6 ft
Diameter of wheel, $D$ , ft	$H - 1.33$ to $H - 2.25$	$3H$ to $4H$	$H + 11.5$ ft	$2H$ to $4H$ (min 14 ft)
Radial depth of buckets, $d$	$0.16 \sqrt[3]{H}$ to $0.25 \sqrt[3]{H}$ <sup>b</sup>	$(0.4 \text{ to } 0.5) \times \sqrt[3]{\frac{D}{H}}$		More than $0.5H$
Number of buckets, $N$	$\frac{\pi D - d}{2Q}$ to $\frac{4Q}{vd}$	$(2 \text{ to } 3) \times \frac{Q}{vd}$		$\frac{12Q}{tv}$
Width of buckets, $b$				
Circumferential velocity, $v$ , fps. . . . .	5 to 7	4.6 to 5.6	5.3 to 7.2	$0.55 \sqrt{2gH}$
Maximum unbraced bucket span, $s$ , ft . . . . .	5.5			
Water jet thickness, $t$ , in. . . . .	2 to 30			8 to 10
Water available, $Q$ , cfs				
Efficiency, $E$ (hydraulic $\times$ mechanical). . . . .	90	85	85	70+

<sup>1</sup> Compiled from MARKS, LIONEL S., "Mechanical Engineers' Handbook," pp. 1341-1342, 4th ed., McGraw-Hill Book Company Inc., New York, 1941.

<sup>a</sup> 10 to 40 ft, economical range of head.

<sup>b</sup> May be up to  $0.5 \sqrt[3]{H}$  where narrow wheel is desired.

cal efficiency. A well-designed wheel should have an efficiency factor  $E$  between 70 and 90 per cent (see Table 10-8) according to design and type. (Note that  $E$  in the above equation is expressed as a decimal.)

**Curvature of Buckets. Overshot Wheels** (Fig. 10-3a). Take  $AB = \frac{1}{3}$  times radial distance  $AC$ , and  $CE = \frac{1}{2}$  times circumferential pitch  $GC$ . Draw  $FE$  at an

angle of 10 to 15 deg with radius  $EH$ . From a point on  $FE$  as a center, describe an arc passing through  $E$  and  $D$  (near  $B$ ), and round this arc into the radial portion  $AB$  of the bucket.

**Breast Wheel** (Fig. 10-3b). From the wheel center  $O$ , draw the dotted circle  $DE$  with a radius equal to the radius of the wheel minus the depth  $F$  of tail water. The outer part  $AB$  of the bucket should be an involute unwrapped from  $DE$ ; the inner part  $AC$  should curve sharply after leaving  $A$ .

**Poncelet Undershot Wheel** (Fig. 10-3c). Draw vertical radius  $OA$  of wheel and lay off  $AC$  and  $AB$  (each 15 deg of circumference), making breast  $BC$ . At mid-depth  $D$  of jet as it strikes the wheel, draw radius  $OD$ ; also draw  $DE$  at an angle of 23 deg to  $OD$ . Take  $DF = 0.5H$  to  $0.7H$  and draw arc  $DG$ , which is the bucket curve desired.

### Water Turbines

Modern practice has narrowed the many possible designs of water turbines down to three accepted characteristic types, the reaction (or overpressure), the impulse (or action), and the underpressure (or suction jet), commonly called the propeller type. All three types have in common a stationary guide case (or nozzle in case of the impulse type) in which the static head is transformed partly, or wholly, into velocity, and a revolving part called the runner with the reaction type, the bucket wheel or wheel with the impulse type, and the runner or propeller with the underpressure type. The development and design of all three types is so far advanced and complex that full explanation cannot be attempted here.<sup>1</sup>

**Popular Types of Water Turbine.** As of 1946, all large turbines built or on order in the United States or Canada were of the Francis, Kaplan impulse, or propeller types (see Table 10-9).

**Francis (reaction) turbines** have normally a radial inlet and discharge the water in a direction more or less parallel to the shaft. Regulation is usually accomplished by wicket-type gates or guide vanes. A single runner is usually preferred for large commercial installations. If the head is under 30 ft, the open-flume type should be used except for small units of less than 100 hp. If the head is 30 to 90 ft, either concrete or steel plate spiral-cased type may be used, depending on local cost conditions. If the head is above 100 ft, cast iron or cast steel is usually used. The only limitation of head is that of the strength of the materials.

**Propeller-type turbines (underpressure)** partly transform the static head into velocity in the guide case and thus discharge a much greater quantity of water than a reaction-type runner of the same discharge diameter and under the same head. The peripheral speed is also far ahead of the reaction type. This turbine is thus best adapted for low heads where large quantities of water must be discharged and where the speed must be as high as possible to economize the cost of a direct-connected generator. They are limited in application to heads that are not so high as to produce cavitation or vibration due to vaporization or vacuum.

**The Kaplan-type turbine** is an adjustable-blade turbine used for conditions similar to a propeller-type turbine when a high average efficiency warrants the additional expense. The runner blades are adjusted by means of an oil-operated piston in the main shaft. The runner blades receive their motion from the turbine governor

<sup>1</sup> The following references are suggested: MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., pp. 1343ff., McGraw-Hill Book Company, Inc., New York 1941. MEAD, "Water Power Engineering," McGraw-Hill Book Company, Inc., New York. LEA, "Hydraulics," Longmans, Green & Co., Inc., New York. BARROWS, H. K., "Water Power Engineering," McGraw-Hill Book Company, Inc., New York, 1943. MERRIMAN, "Hydraulics," John Wiley & Sons, Inc., New York. DAUGHERTY, R. L., "Hydraulics," 4th ed., McGraw-Hill Book Company, Inc., New York, 1937. DAUGHERTY, R. L., "Hydraulic Turbines," 3d ed., McGraw-Hill Book Company, Inc., New York, 1920. GIBSON, "Hydraulics and Its Applications," D. Van Nostrand Company, Inc., New York.

through a cam mechanism so designed that the runner blades move in proper relationship to the guide vanes to obtain maximum efficiency.

**Impulse turbines** are designed with a runner in the form of a disk, upon the rim of which buckets are mounted, these buckets usually being of the double-lobe form, the

**Table 10-9. Water Wheels Built or on Order in the United States and Canada in 1946<sup>1</sup>**

Type.....	Francis	Propeller	Kaplan	Impulse
Number of plants using	112	22	16	3
Water-wheel capacity, hp:				
Range of unit sizes. . .	49-165,000	107-45,000	406-44,000	3,650-62,500
Avg unit size.....	27,670	14,641	16,581	34,550
Water-wheel speed, rpm:				
Range of speeds	75-1,200	78-450	80-250	225-514
Avg speed	262	145	180	335
Design head, ft:				
Range of heads	7-523	9-56	14-76	920-1,223
Avg head. ....	146	36	43	1,091

<sup>1</sup>Power, June, 1947, pp. 74-77.

**Table 10-10. General Characteristics of Water Turbine Installations<sup>1</sup>**

Setting and construction	No. of runners	Usual head limits, ft
Reaction turbines, 5- to 1,000-ft head		
Open flume, 5- to 40-ft head:		
Vertical.....	1	5-40
	2	15-40
Horizontal	1	12-40
	2	16-40
	4	16-30
	6	16-25
Encased, 15- to 1,000-ft head:		
Plate steel:		
Vertical.....	1	40-300
Horizontal .	1	30-100
	2	30-100
Concrete, vertical	1	15-50
Concrete, spiral, vertical	1	15-90
Cast or welded plate, steel spiral:		
Vertical .....	1	75-1,000
Horizontal....	1	50-600
	2	50-500
Impulse wheels, 500- to 3,000-ft head		
Horizontal:		
Stationary nozzle..	1	500-3,000
Jet deflectors..	2	500-1,500

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 1347, McGraw-Hill Book Company, Inc., New York, 1941.

two parts coming together in a common splitter. Tangent to the runner, one or more water jets impinge upon the splitters of the buckets and are diverted approximately 90 deg from their initial absolute direction. The static pressure is here completely transformed into velocity, so that atmospheric pressure surrounds both the jet, issuing from the nozzle, and the bucket wheel. The jet is usually circular in section and

is adjusted by moving a needle which is concentric with the axis of the nozzle. For a given head and diameter, the impulse-type runner cannot revolve so fast as the reaction-type runner. For the purpose of obtaining higher speeds in connection with moderate heads, or for extremely large units, a plurality of jets per wheel may be used, although this sacrifices simplicity of design. The principal application of impulse turbines is with very high heads (1,500 to 3,000 ft).

Modifications of reaction and impulse turbines, including Girard wheels, Fourneyron wheels, and Jonvil wheels, are not now in general use because of inherent disadvantages as to size, cost, efficiency, durability, or regulation, which make them uneconomical or impractical.

### Hydroelectric Power in the United States and Canada<sup>1</sup>

As is shown in Fig. 10-4, hydroelectric power has grown rapidly and steadily in both the United States and Canada since the First World War.

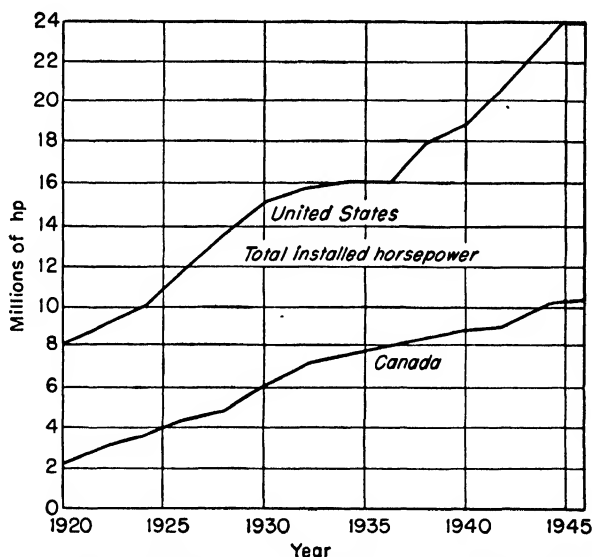


FIG. 10-4. Total installed hydroelectric horsepower in the United States and Canada. (*Power*, June, 1947.)

In the United States, most of the more important plants have been or are being installed by U.S. Bureau of Reclamation, U.S. Engineer Corps, and Tennessee Valley Authority.

On the Missouri River about 100 dams are to be constructed to provide more than 100,000,000 acre-ft of storage. Eight important dams and their power plants are completed, and an equal number are under construction. Among the completed dams, that at Fort Peck is the largest earth-fill dam in the world. Other comparable dams either under construction or being planned by U.S. Engineer Corps are Garrison, Oane, and Fort Randall.

The Columbia River development is the greatest of all government projects, with two huge plants in operation: Bonneville is completed with 729,000 hp; Grand Coulee now has 928,000 hp in six main units with six more units on order. This plant will have an ultimate rating of 3,012,000 hp.

<sup>1</sup> *Power*, June, 1947, pp. 73-78.



Table 10-11. Water-power Plants in the United States of Over 100,000 Hp Installed Capacity<sup>1</sup>

Rank	Owner	State	River	Dam	Installed hp <sup>2</sup>
1	U.S. Bureau of Reclamation	Ariz.-Nev.	Colorado	Boulder	1,435,000
2	U.S. Bureau of Reclamation	Wash.	Columbia	Grand Coulee	928,000 <sup>a</sup>
3	U.S. Engineer Corps.	Ore.-Wash.	Columbia	Bonneville	729,000
4	Tennessee Valley Authority	Ala.	Tennessee	Wilson	470,000
5	Niagara Falls Power Co.	N.Y.	Niagara	Schoellkopf	454,500
6	U.S. Bureau of Reclamation	Calif.	Sacramento	Shasta	419,000 <sup>b</sup>
7	Susquehanna Power Co.	Md.	Susquehanna	Conowingo	378,000
8	U.S. Bureau of Reclamation	Ariz.-Nev.	New Colorado	Davis	311,000
9	Safe Harbor Water Power Co.	Pa.	Susquehanna	Safe Harbor	255,000
10	Lexington Water Power Co.	S.C.	Saluda	Saluda	220,000
11	Connecticut River Power Co.	N.H.	Connecticut	Comerford	216,000
12	Tennessee Valley Authority	Tenn.	Tennessee	Watts Bar	210,000
13	U.S. Engineer Corps	Ky.	Cumberland	Wolf Creek	207,000
14	Union Electric Co. of Mo.	Mo.	Osage	Osage	201,000
15	Tennessee Valley Authority	Tenn.	Tennessee	Pickwick	192,000
16	City of Seattle	Wash.	Skagit	Diablo	191,000
17	U.S. Engineer Corps	N.C.	Little Tennessee	Fontana	183,000
18	Tennessee Valley Authority	Ala.	Tennessee	Wheeler	180,000 <sup>c</sup>
19	Tennessee Valley Authority	Ky.	Tennessee	Kentucky	176,000 <sup>d</sup>
20	South Carolina Public Service Authority	S.C.	Santee	Santee-Cooper	173,000
21	Alabama Power Co.	Ala.	Coosa	Jordan	164,000
22	U.S. Bureau of Reclamation	Ariz.-Calif.	Colorado	Parker	160,000
23	Pennsylvania Water & Power Co.	Pa.	Susquehanna	Holtwood	158,000
24	Missouri River Power Co.	Iowa	Mississippi	Keokuk	150,000
25	Carolina Power & Light Co.	N.C.		Waterville	147,000
26	Alabama Power Co.	Ala.	Tallapoosa	Martin	144,000
27	Electro Metallurgical Co.	W. Va.		Hawks Nest	140,000
28	U.S. Engineer Corps	Tenn.	Carney Fork	Center Hill	138,000
29	Tennessee Valley Authority	Tenn.	Tennessee	Norris	132,000
30	South California Edison	Calif.		Big Creek 2	124,400
31	South California Edison	Calif.		Big Creek 3	122,700
32	City of Seattle	Wash.		Gorge	114,975
33	Alabama Power Co.	Ala.	Coosa	Lay	114,000
34	Aluminum Co of America	Tenn.		Calderwood	112,000
35	Georgia Power Co.	Ga.		Tallulah	111,600
36	Tennessee Valley Authority	Tenn.	Tennessee	Chickamauga	108,000
37	Carolina Aluminum Co.	N.C.		Narrows	108,000
38	Louisville Gas & Electric Co.	Ky.		Ohio Falls	108,000
39	South California Edison	Calif.		Big Creek 1	106,000
40	Tennessee Valley Authority	Tenn.	Hiwassee	Appalachia	106,000
41	Niagara Falls Power Co.	N.Y.	Niagara	Edw. Dean Adams	105,000
42	Duke Power Co.	S.C.	Wateree	Wateree	105,000
43	Appalachian Electric Power Co.	Va.		Claytor	104,000
44	U.S. Engineer Corps	Ga.	Etowah	Allatoona	102,900
45	Tennessee Valley Authority	Ala.	Tennessee	Guntersville	102,000
46	City of Los Angeles	Calif.		S. Francisquite	101,460
47	San Francisco Public Utility Commission	Calif.		Moccasin Creek	100,000
48	Grand River Dam Authority	Okl.	Grand	Pensacola	100,000

<sup>1</sup> "Water Power Plants in the U.S.A.," Federal Power Commission Document 125, 1939; *Power*, June, 1947.<sup>2</sup> Horsepower on order in addition to power listed: (a) 945,000; (b) 103,000; (c) 90,000; (d) 44,000.

The Tennessee Valley project of the Tennessee Valley Authority is now virtually completed. Its various plants produced 12,314,000,000 kwhr in 1946.

In Canada, outstanding new plants include Des Jöachims of the Hydro Electric Power Commission of Ontario on the Ottawa River, the Shawinigan No. 3 plant of the Shawinigan Water and Power Co., the Bridge River plant of the British Columbia

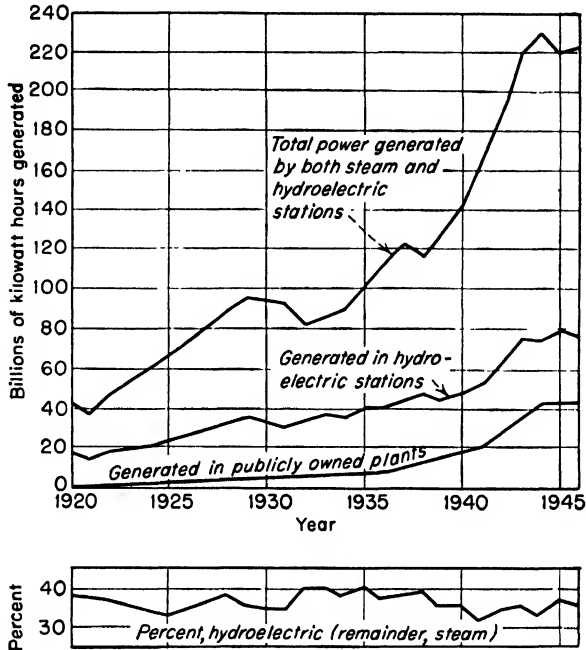


FIG. 10-5. Total and hydroelectric power generated in the United States, 1920 to 1946. (*Power*, June, 1947.)

Electric Co., designed for ten 62,000-hp units under a 1,130 ft head, and a fourteenth 53,000-hp unit for the Quebec Beauharnois plant.

### POWER FROM OCEAN WAVES

The energy of a wave depends upon such factors as shape, height, length between crests, and distance perpendicular to forward motion.

According to Albert W. Stahl, USN (*Trans. ASME*, vol. 13, p. 438), the total energy of a series of trochoidal deep-sea waves may be expressed as follows:

$$\text{Hp/ft of breadth of wave} = 0.0329H^2 \sqrt{L} \left[ 1 - 4.935 \left( \frac{H^2}{L^2} \right) \right]$$

where  $H$  = height of wave, ft

$L$  = length of wave between successive crests, ft

**Example.** (1) With  $L = 25$  ft and  $L/H = 50$ ,  $\text{hp} = 0.04$ . (2) With  $L = 100$  ft and  $L/H = 10$ ,  $\text{hp} = 31.3$ .

Actually not more than one-fourth of the total energy of such waves would probably be available after reaching shallow water because of conversion of a large part of the energy to turbulence, and of this one-fourth only about one-third would probably be available with apparatus sufficiently rugged for this type of service.

Wave motors thus far tried have been based either on the lifting power of the waves to raise floats or upon the backward and forward motion of swinging paddles.

An experimental motor on an Atlantic City pier had six 2,100-lb 4 ft diameter by 4 ft high cylindrical floats driving a horizontal shaft by chains and ratchets, equalized by flywheels. The floats were lifted 2 ft eleven times a minute to develop about 12 hp.

### Tidal Power

The more practical of the several plans that have been advanced for the utilization of the tides for the generation of power employ one or more tidal basins, so arranged that a tidal head is always available for the operation of water wheels or turbines. A tidal range of 6 ft is considered a minimum practical working head. A brief description of the leading schemes follows:

1. A single basin with the turbines operating only after the tide has fallen away from the crest of the turbine-containing dam a sufficient distance to create the head desired. A marked disadvantage of this type is that power can be generated only intermittently, usually for a maximum of 6 or 7 hr out of the 24.

2. A single basin with the turbines operating on both the rising and falling tides. With a working head equal to one-half of the tidal range, the time of operation and the power generated are both about 60 per cent greater than system 1.

3. Two basins with turbines in the dividing wall so operated that one basin is never allowed to fall below one-third of the tidal range and the other is never allowed to rise above one-third of the range. In this fashion, which is made possible by means of sluice gates to the ocean, a working head of  $0.55$  to  $0.80H$  ( $H$  = tidal range) is always available for the continuous operation of the turbines. However, the cost per horsepower is apt to be high, and the output will only be about one-half of that of system 1 and one-third of that of system 2.

4. Two tidal basins with an upper basin discharging to the sea through turbines, and the sea filling the lower basin through a second set of turbines. Periodically the upper basin is filled, and the lower basin emptied, through sluice gates. Head varies between  $0.25H$  and  $0.60H$ ; output is some 25 per cent greater than system 3; and operation is constant but at the expense of the second set of turbines.

**Power Available.** According to J. Royden Pierce (*Eng. News-Record*, Jan. 27, 1912), the maximum number of horsepower-hours obtainable from a tidal basin is

$$N = \frac{HQ - (Q^2/2A)}{31,800}$$

where  $H$  = tidal head or range (total), ft

$Q$  = available drop in the level of the basin, ft, multiplied by the area  $A$  of the basin, sq ft

$A$  = area of the basin, sq ft

**Extant and Proposed Installations.** To prove economical tidal power requires a rather rare combination of (1) large impounding areas, (2) high tidal range, (3) minimum difference between neap and spring tides, and (4) proximity to demand for power. An existing installation is at Mamaroneck, N.Y., where 1,200,000 sq ft and a 7-ft tide generate 330 hp for  $6\frac{3}{4}$  hr, with an average drop of 1.4 ft, for an average of about 50 hp.

Leading, proposed, but unaccomplished installations are topped by Passamaquoddy Bay, where it has been estimated that the impounding of tidal rivers would produce some 600,000 hp from a tidal range of 23.2 ft, and a neap range of some 55 per cent of the spring range; the general Bay of Fundy area, where the average spring tidal range is some 45.5 ft; the Shepody Bay area (Bay of Fundy) with estimated potentialities of 200,000 hp; the Severn River in England; and the Brittany coast in France.

## WIND AS A SOURCE OF POWER

Wind has been used for the generation of power since at least A.D. 1100. At the present time, the simplicity and low cost of small gasoline engines has relegated the use of wind to certain small water-pumping installations and battery-charging dynamo sets. Nevertheless such a tremendous amount of potential energy is available that wind cannot be overlooked as a source of power.

**Wind Available in the United States.** Figure 10-6 shows the annual average wind velocity for the United States. U.S. Weather Bureau records at Dayton, Ohio, showed the following general characteristics of ordinary winds:

1. In each month, there is a well-defined group of wind velocities which predominate and may be called the prevalent or frequent winds; in addition, there is a group of winds containing the bulk of the month's wind energy, called energy winds.

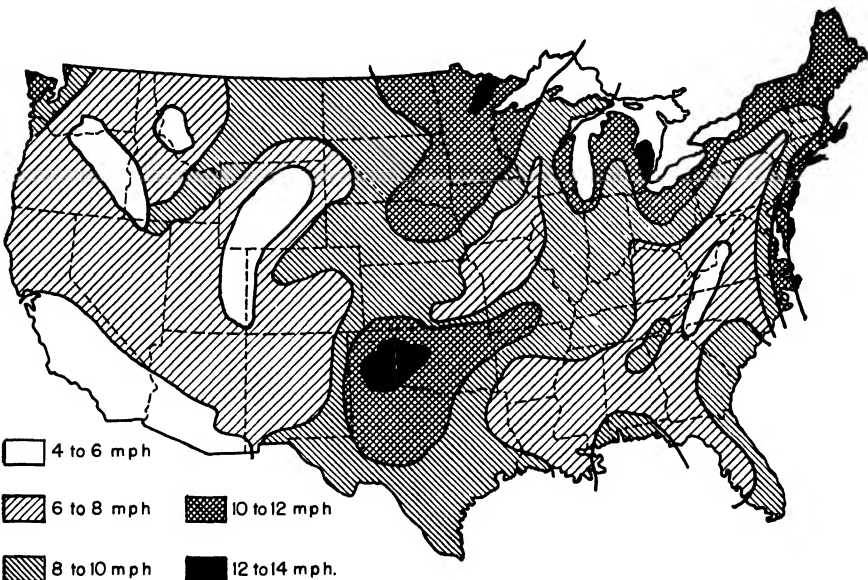


FIG. 10-6. Average annual wind velocity in the United States. (U.S. Weather Bureau.)

2. The energy winds produce about three-fourths of the total energy available in a given month. Even in a calm summer month, 70 per cent of the energy comes from winds blowing only 42 per cent of the time.

3. Energy winds blow 2 out of 7 days; prevalent winds 5 out of 7 days.

4. The mean prevalent wind velocity is 2 mph less than the average monthly velocity.

5. The energy winds blow at velocities of about 2.3 times those of the prevalent winds.

6. The wind of highest energy has about 10 mph greater velocity than the most frequent wind.

7. About the minimum wind velocity practical for the propeller-type wheels is 8 mph. The ability to use wind velocities down to about 6 mph, as with light multi-blade wheels, results in about 14 per cent greater capacity than if the minimum of 8 mph is in effect.

8. The ratio of the windiest to the calmest month is about 7:4. Energy in kilowatt-hours is about  $4\frac{1}{2}$  times greater in the windiest month. To hold the power constant through the year, a regulating device must spill three times as much energy as is used.

**Selecting a Site for Wind-power Devices.** According to Thomas,<sup>1</sup> some assistance in the search for wind-turbine sites may be obtained by studying the physiographic characteristics of the area in question, which should be one in which there is an observed tendency to windiness. It is helpful to imagine the wind as a vast stream of water flowing over the surface of the country like a river. Looking at a brook or rapid river, the "fast water" is seen to run between stones and over obstructions on the bottom, and where the slope is the steepest; it is the same with the wind.

It may be assumed that several of the following factors may be acting simultaneously:

1. The highest average wind will occur when there is the least surface obstruction, considered over a wide area, such as the ocean or a large lake.

2. Velocity of the wind will tend to be high on down slopes due to gravity, as with water.

3. Where there are many houses, trees, and unevenness in the ground surface, the wind will tend to be slowed down, this effect extending to elevations above the ground many times the height of the obstruction.

4. A single isolated obstruction tends to cause an increase in the velocity of the air locally without greatly affecting the over-all stream velocity. Such isolated obstructions are favorable to fringes of high wind velocities. If the obstruction is narrow and high, the wind will go around both sides of it. If it is long and low, like a rolling hill, the wind will speed up over the top.

5. Streamline flow, as distinguished from turbulence, is very important and is difficult to find in wind near the ground.

6. Because of the resistance at the surface of the ground, the velocity of the wind is greater at higher and higher levels, more or less in what is known as a "logarithm" ratio. In open flat country, balloon measurements are said to have shown an average increase in velocity of some 40 per cent at about 500 ft above the ground, with further increases still higher. Note this is considerably more than would be calculated from the formula that follows, also secured from balloon measurements but considerably older. In the absence of further measurements, it can be assumed that the greater increase in velocity occurs largely as a result of breaking away from the immediate retarding effect of the earth's surface (*i.e.*, at lower altitudes) and that the formula will apply from there on up in altitude.

#### Variation of Wind Velocity with Altitude<sup>2</sup>

Experiments with pilot balloons at McCook field (1921 to 1922) indicated that the wind velocity at altitudes up to 5,000 ft can be represented by the following equations:

$$V = \left( \frac{h}{2,400} + 1 \right) V_1 \quad \text{for average winds}$$

$$V = \left( \frac{h}{8,550} + 1 \right) V_1 \quad \text{for highest winds observed}$$

where  $V$  = velocity, mph, at an altitude  $h$

$V_1$  = velocity, mph, near the ground

$h$  = height, ft aboveground

<sup>1</sup> THOMAS, PERCY H., Federal Power Commission, as reported in *Mech. Eng.*, September, 194 pp. 742-743.

<sup>2</sup> "Custodis Chimneys," Alphons Custodis Chimney Construction Co., New York, 1924.

### Pressure Exerted by Wind<sup>1</sup>

The determination of the pressure exerted by wind of a given velocity on a given surface has long been a subject of controversy. Several values have been assigned. The reason is that the airfoil effect of different shapes and surfaces is so different that the exact force cannot be determined in any way short of actual measurement.

The method in the past has been to determine values for flat surfaces and then to apply a correction factor for various forms of profile. The equation for pressure on flat surfaces normal to the direction of the wind may be expressed as

$$P = C \times v^2$$

where  $P$  = lb pressure/sq ft

$v$  = wind velocity, mph

$C$  = a constant which has been assigned values ranging from 0.00214 to 0.00535 by various investigators of reliable standing (the weighted average of 0.0033 is probably sufficiently close for most practical purposes)

Using the weighted average for  $C$  of 0.0033, a solution of this equation for various wind velocities is as shown in Table 10-12.

To convert the above pressures on flat surfaces to pressure on round surfaces, such as chimneys, American engineers use a factor of  $\frac{1}{2}$  to  $\frac{3}{4}$ , continental engineers use  $\frac{2}{3}$ ; for octagonal surfaces Americans use 0.75, continental engineers, 0.71.

### Windmills

**Types of Windmill.** Classified roughly according to speed, there may be said to be three types of windmills in common use: (1) the slow-speed type, as exemplified by the American multiblade wheel; (2) the medium-speed type, like the familiar sweepsail four-bladed Dutch mill; and (3) the high-speed type, such as two- and four-bladed airplane-type propellers.

Slow-speed wheels must be geared up for electric generation, and thus find their greatest application in pumping water. Medium-speed wheels have not been used for electric generation to any considerable extent. High-speed wheels of the propeller type characteristically have a low starting torque and must be connected to such constant loads as plunger pumps through suitable throwout clutches. Otherwise, high-speed wheels have the advantages of greater efficiency, less gearing needed to generators, small blade areas with less hazard in storms, and simplicity.

**Speed of Blades.** The term speed in connection with a windmill refers to the circumferential speed of the tips of the blades. It is customary to compare this tip speed with that of the wind causing rotation. The factor  $U/V$  is the common expression for this ratio. ( $V$  denotes the wind speed;  $U$  the circumferential tip speed corresponding to  $V$  wind speed.) Table 10-13 shows characteristic speeds for several types of wheels.

**Efficiency.** Several formulas are available for calculating the probable power from a windmill. Of these, the following is a simple approximation, sufficiently close for most purposes, particularly in the smaller applications:

$$Hp \text{ exerted by the wind on the wheel} = 0.00000226AV^3$$

<sup>1</sup> *Ibid.*

**Table 10-12. Pressure on Surfaces Normal to the Wind**

Wind velocity, mph	Shape of surface	
	Flat	Round*
5	0.08	0.06
10	0.33	0.22
20	1.32	0.88
30	3.00	2.00
40	5.28	3.54
50	8.25	5.53
60	11.88	7.96
70	16.17	10.83
80	21.12	14.08
90	26.73	17.82
100	33.00	22.00

NOTE: Figures in body of table are pressures in pounds per square foot of surface normal to the wind.

\* Round surfaces calculated at two-thirds those of flat surfaces.

where  $A$  = whole area, sq ft, enclosed by the circumference described by the wind wheel

$V$  = wind speed, fps

In order to obtain the ultimate power from the particular windmill, it is necessary to multiply the total force of the wind, as obtained from the above formula, by the efficiency of the apparatus. As is illustrated in Table 10-13, this efficiency will range from about 22 to 42 per cent, according to the type of wheel, etc.

**Effect of Size on Economics.** In the design of windmills, all linear dimensions are in proportion to the wheel diameter  $D$ . The area of the wheel and the power of the mill increase as  $D^2$ , but the material required and consequent weight and cost increase as  $D^3$ . As a result, the cost of power is proportionately greater for a large mill than for a small mill; the reverse of general prime-mover economics. Thus a number of small mills could be installed for less to produce the same power as one large mill. American windmills, originally 25 ft and larger, now range from 6 to 16 ft, with 8 ft predominating.

The outstanding experimental effort with large-scale wind-power generation in the United States was that of the Central Vermont Public Service Corp. A 1,000-kwhr unit was installed on 2,000-ft Grandfather's Knob, near Rutland. Principal dimen-

Table 10-13. Typical Efficiencies and Speeds of Various Rotors<sup>1</sup>

Type wheel	Range of tip speed, $U/V$	Point of best efficiency	
		Efficiency, per cent	Tip speed $U/V$
Slow-speed wheels, multiblade with concave metal blades	1 0-1 5	33	1 17
Medium-speed wheels, Dutch type, sweep sails . . .	1 5-3 0	22	2 00
High-speed wheels:			
4-blade type (propeller)	3 0-6 0	42	3 10
2-blade type (propeller)		36	4 30

<sup>1</sup> SABININ, G., Problems of Utilizing the Energy of the Wind, *Trans. Central Aero-hydrodynamical Institute, Moscow*, 1926.

sions were about as follows: tower, 107 ft high; wheel, two-blade airplane type, 175-ft span; all motions of rotation, pitching, yawing, etc., automatically controlled; speed constant at 28.7 rpm with tip speed of 15,785 fpm; 20-mile wind needed for appreciable power generation. While the unit was ultimately destroyed and not rebuilt, all results have been faithfully recorded in "Power from the Wind" by Palmer C. Putnam.<sup>1</sup> Mr. Putnam was the inventor and designer of the Smith-Putnam wind turbine used in the experiments.

**Proposed Larger Commercial Installation.** In discussing the Smith-Putnam turbine, Thomas<sup>2</sup> has proposed and presented plans for a 7,500-kw wind turbine. Thomas proposes two wheels, each 200 ft in diameter, located on the two ends of a 235-ft bridge, revolving on a turntable located on the top of a 475-ft tower. These wheels are to have three blades each, fixed in position in the hub, but without the feathering feature. On account of the terrific aerodynamic thrust on these blades due to their high speed, 550 fps at the tip, a tension brace leading from the hub is provided for each blade to give it sufficient strength. The two blades are geared to a single shaft to drive a direct-current generator.

<sup>1</sup> D. Van Nostrand Company, Inc., New York.

<sup>2</sup> THOMAS, PERCY H., Federal Power Commission, paper before United Nations Scientific Conference on the Conservation and Utilization of Resources, at Lake Success, N.Y. (Reported in *Mech. Eng.*, September, 1949, pp. 742-743).

The high tower is said to be desirable for two principal reasons: (1) the wheel of a high-speed turbine draws on a cylinder of wind several times the diameter of the wheel and thus benefits from free clearance; and (2) the velocity of the wind and its smooth streamline character are definitely improved as the altitude increases. In this connection, it is important to note that, as the energy content of wind increases as the cube of its velocity, any increase in velocity is greatly magnified in effect. Moreover, Thomas estimates that the cost of a 500-ft tower would be less than 25 per cent of the total aerogenerator cost.

**Table 10-14. Kilowatts Generated by Propeller-windmill Electric Plants<sup>1</sup>**

Wheel diam, ft	Velocity of wind, mph						
	8	10	12	16	20	25	30
12	0 04	0 09	0 15	0 35	0 69	1 36	2 32
14	0 06	0 12	0 20	0 48	0 93	1 83	3 16
16	0 08	0 15	0 26	0 63	1 22	2 39	4 12
18	0 10	0 19	0 33	0 79	1 54	3 02	5 22
20	0 12	0 24	0 41	0 98	1 91	3 73	6 45
25	0 19	0 37	0 64	1 53	2 98	5 83	10 06
30	0 27	0 53	0 93	2 19	4 29	8 39	14 48
35	0 37	0 73	1 26	2 98	5 83	11 40	19 70

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," p. 1136, McGraw-Hill Book Company, Inc., New York, 1941.

### SOLAR HEAT<sup>1</sup>

**Magnitude of Solar Radiation.** If a plane surface were set perpendicular to the rays of the sun (*e.g.*, for normal incidence) outside the earth's atmosphere, it would receive solar radiation of about 420 Btu/hr/sq ft. A similar receiving surface on the surface of the earth would receive radiant energy at a considerably lower rate because a large part of the radiation entering the atmosphere is scattered in passing through the air, moisture, smoke, and dust which comprise the earth's envelope. Also, some of the atmospheric constituents, notably water vapor, carbon dioxide, and ozone, absorb radiant energy. This absorption and scattering cause different proportionate reductions from outer-atmosphere radiation intensity with different wave lengths. The important principle to remember is that the radiation reaching the surface of the earth is the sum of  $I_n$  and  $I_s$ , where  $I_n$  is the direct radiation (at normal incidence, which is the transmitted fraction of the net sun radiation received by the outer atmosphere) and  $I_s$  is the sky or diffuse radiation coming from the atmosphere itself as a consequence of the scattering and adsorption which give rise, in part, to a reradiation to the earth. The diffuse radiation does not strike only at normal incidence; it strikes at all angles from which the sky sees the surface in question.

Standardized practical-purpose values of the direct radiation incident upon a plane perpendicular to the sun's rays at the earth's surface have been proposed by P. Moon. Table 10-15 gives these data. They are representative of a clear day at about sea-level elevation. For industrial areas,  $I_n$  values will be slightly lower than this table, with the greatest decrease occurring at low solar altitudes toward evening.

Practical design data on sky radiation are meager. Table 10-15 presents a basis of estimates for clear summer days in terms of the direct solar radiation to sky radiation ratio.

<sup>1</sup> "1949 Heating, Ventilating & Air Conditioning Guide," Chap. 15, pp. 280-281, ASHVE. Used by permission.



In the usual application, the receiving surface will not be perpendicular to the rays of the sun. The intensity of the direct radiation incident upon a surface (Btu per hour per square foot of absorbing surface) which is oriented with an angle of incidence for the sun's rays is

$$I_d = KI_n$$

where  $I_d$  = intensity of incident direct radiation, Btu/hr/sq ft

$I_n$  = intensity of direct radiation on a plane normal to the sun's rays, Btu/hr/sq ft, from Table 10-16

$K$  = cosine of the angle of incidence  $\theta$

The angle of incidence (see Fig. 10-7) is the angle between the sun's rays and the normal to the absorbing surface.

The solar altitude is the angle (Fig. 10-7) between the sun's rays and the horizontal.

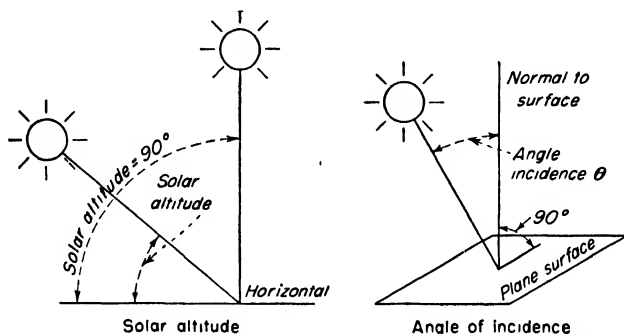


FIG. 10-7. Definition of solar altitude and angle of incidence. (ASHVE Guide, 1949.)

For horizontal surfaces, the magnitude of  $K$  is determined by the time of the year, the time of the day (sun's position), and the latitude of the location concerned. Complete tabulated calculations are available for magnitudes of the factor  $K$ , for all needed conditions. Illustrative excerpts are given in Table 10-17.

It must be noted that values for  $K$  as given in Table 10-17 include only the direct radiation; sky radiation must be calculated separately and added to the direct radiation (see Table 10-15).

Table 10-15. Approximate Ratio of Direct Solar Radiation to Sky Radiation Received on a Horizontal Surface on Clear Days in Eastern States<sup>1</sup>

Solar altitude, deg	Ratio	Solar altitude, deg	Ratio	Solar altitude, deg	Ratio
10	1 40	40	3 84	70	5 63
20	2 30	50	4 55	80	5 90
30	3 10	60	5.20	90	6 10

<sup>1</sup> "Heating, Ventilating, & Air Conditioning Guide," Chap. 15, p. 280, ASHVE, 1949.

**Solar Irradiation of Surfaces Facing South.**<sup>1</sup> Table 10-19 shows the sun's position vertically and horizontally for four United States latitudes for different hours of the

<sup>1</sup> HUTCHINSON, F. W., Solar Irradiation of Walls and Windows South-facing: October-April, *Heating, Piping Air Conditioning*, vol. 21, No. 7, pp. 102-104, July, 1949. Mr. Hutchinson's material is from a project on solar heating sponsored by the Libbey-Owens-Ford Glass Co. and carried on at Purdue University in cooperation with the Purdue Research Foundation.

**Table 10-16. Direct Solar Radiation Received at Normal Incidence at the Earth's Surface at Sea Level<sup>1</sup>**

(I <sub>n</sub> )					
Solar altitude, deg	I <sub>n</sub> , Btu/hr/sq ft	Solar altitude, deg	I <sub>n</sub> , Btu/hr/sq ft	Solar altitude, deg	I <sub>n</sub> , Btu/hr/sq ft
5	65	30	234	60	276
10	122	35	245	70	283
15	165	40	253	80	289
20	196	45	260	90	294
25	219	50	266		

<sup>1</sup> "Heating, Ventilating, & Air Conditioning Guide," Chap. 15, p. 280, 1949. As an approximate altitude correction, add 1 per cent for each 1000 ft of altitude.

**Table 10-17. Values of K for Horizontal Planes in North Latitudes during the Period May 2 to Aug. 10<sup>1,a</sup>**

Local mean sun time <sup>b</sup>		North latitude, deg					
A.M.	P.M.	25	30	35	40	45	50
5	7	0 145	0 171	0 196	0 034	0 070	0 106
6	6	0 145	0 171	0 196	0 220	0 242	0 262
7	5	0 365	0 382	0 395	0 406	0 414	0 418
8	4	0 570	0 578	0 581	0 580	0 574	0 564
9	3	0 747	0 746	0 740	0 729	0 712	0 689
10	2	0 882	0 876	0 862	0 843	0 817	0 785
11	1	0 967	0 957	0 940	0 915	0 834	0 845
Noon		0 996	0 985	0 966	0 940	0 906	0 866

<sup>1</sup> "Heating, Ventilating, & Air Conditioning Guide," p. 283, ASHVE, 1949.

<sup>a</sup> Figured for solar declination of 20 deg.

<sup>b</sup> The relation between local mean sun time and civil time may be obtained from weather Bureau offices.

**Table 10-18. Relation between Local Mean Sun Time and Solar Altitude during the Period May 2 to Aug. 10, North Latitudes<sup>1</sup>**

Local mean sun time		Solar altitude					
		North latitude, deg					
A.M.	P.M.	25	30	35	40	45	50
5	7	0	0	0	2	4	6
6	6	8 5	10	11	12 5	14	15
7	5	21 5	22 5	23 5	24	24 5	24 5
8	4	35	34 5	35 5	35 5	35	34 5
9	3	48 5	48	47 5	47	45 5	43 5
10	2	62	61	59 5	57 5	55	51 5
11	1	75 5	73	70	66	62	57 5
Noon		85	80	75	70	65	60

<sup>1</sup> "Heating, Ventilating, & Air Conditioning Guide," p. 284, ASHVE, 1949.

day from October through April. They also include hourly intensity of the rays normal to the sun's angle and instantaneous irradiation on a unit area of a vertical south-facing surface.

The hourly data in each table are based on exact conditions for the twenty-first day of the month in question, but for usual engineering computations they can be used with adequate accuracy for any other day of the same month. The conditions

Table 10-19. Solar Irradiation of Vertical Surfaces Facing South<sup>1</sup>

Solar time		Solar altitude	Azimuth	180 - A	Angle of incidence	Btu/hr /sq ft	Instantaneous irradiation, Btu
A.M.	P.M.	H	A	B	i	i <sub>o</sub>	i <sub>o</sub> cos i
Latitude 30° <sup>a</sup>							
October:							
8	4	18	117	63	64 42	247 2	106 7
9	3	29	127	53	58 24	279 0	146 8
10	2	39	141	39	52 85	295 4	178 4
11	1	46	158	22	49 90	305 1	196 5
Noon		49	180	0	49 00	307 0	201 4
November:							
8	4	13	123	57	57 95	214 9	114 0
9	3	24	133	47	51 47	269 6	168 0
10	2	32	147	33	44 67	288 2	205 0
11	1	38	162	18	41 45	298 0	223 3
Noon		40	180	0	40 00	301 0	230 6
December:							
8	4	11	125	55	55 74	192 7	108 5
9	3	21	136	44	47 82	264 9	177 9
10	2	29	148	32	42 12	285 7	211 8
11	1	35	163	17	38 44	296 5	232 2
Noon		37	180	0	37 00	299 5	239 2
January:							
8	4	13	123	57	57 95	220 0	116 7
9	3	24	133	47	51 47	276 0	171 9
10	2	32	147	33	44 67	295 0	209 8
11	1	38	162	18	41 45	305 0	228 6
Noon		40	180	0	40 00	308 0	235 9
February:							
8	4	18	117	63	64 42	253 0	109 2
9	3	29	127	53	58 24	285 7	150 4
10	2	39	141	39	52 85	302 5	182 7
11	1	46	158	22	49 90	312 4	201 2
Noon		49	180	0	49 00	314.3	206 2
March:							
7	5	10	97	83	83 10	183 7	22 0
8	4	25	105	75	76 44	273 6	64 1
9	3	37	106	64	69 51	296 0	103 6
10	2	49	130	50	65 06	310 7	131 0
11	1	56	152	28	60 42	314 6	153 3
Noon		60	180	0	60.00	315.6	157 8
April:							
6	6	6	79	101			
7	5	20	87	93			
8	4	32	96	84	84 92	284 8	25 2
9	3	44	105	75	79 28	303 2	56 4
10	2	56	118	62	74 78	310 9	81 6
11	1	66	140	40	71 85	315 7	98 3
Noon		71	180	0	71 00	318 6	103 7

NOTE: The original article includes all latitudes; only those of the United States are included here.

<sup>1</sup> HUTCHINSON, F. W., Solar Irradiation of Walls and Windows Facing South, *Heating, Piping Air Conditioning*, July, 1949, pp. 102-104.<sup>a</sup> Approximates Jacksonville, New Orleans, Houston, San Antonio.

Table 10-19. Solar Irradiation of Vertical Surfaces Facing South.<sup>1</sup> (Continued)

Latitude 35°

Solar time		Solar altitude	Azimuth	180 - A	Angle of incidence	Btu/hr /sq ft	Instantaneous irradiation, Btu
A.M.	P.M.	H	A	B	i	i <sub>0</sub>	i <sub>0</sub> × cos i
October:							
8	4	17	118	62	63.32	239.4	107.5
9	3	27	128	52	56.73	275.2	151.0
10	2	36	143	37	49.75	291.6	188.4
11	1	41	160	20	44.83	299.3	212.3
Noon		44	180	0	44.00	303.2	218.0
November:							
8	4	11	124	56	56.71	190.5	218.0
9	3	21	135	45	48.69	261.8	172.8
10	2	28	148	32	41.52	281.4	210.7
11	1	32	163	17	35.82	288.2	233.7
Noon		35	180	0	35.00	293.1	240.1
December:							
8	4	10	126	54	54.62	185.8	107.6
9	3	17	137	43	45.63	245.1	171.4
10	2	24	149	31	38.46	272.8	213.6
11	1	29	164	16	32.79	285.7	240.2
Noon		31	180	0	31.00	291.6	250.0
January:							
8	4	11	124	56	56.71	195.0	107.0
9	3	21	135	45	48.69	268.0	176.9
10	2	28	148	32	41.52	288.0	215.6
11	1	32	163	17	35.82	295.0	239.2
Noon		35	180	0	35.00	300.0	245.7
February:							
8	4	17	118	62	63.32	245.1	110.1
9	3	27	128	52	56.73	281.7	154.5
10	2	36	143	37	49.75	298.5	192.9
11	1	41	160	20	44.83	306.4	217.3
Noon		44	180	0	44.00	310.4	223.3
March:							
7	5	10	98	82	82.12		
8	4	24	108	72	73.60	269.6	76.1
9	3	33	120	60	65.82	293.1	120.1
10	2	45	134	46	60.58	307.7	151.1
11	1	52	155	25	56.10	310.7	173.4
Noon		56	180	0	56.00	314.6	175.9
April:							
6	6	7	80	100			
7	5	20	90	90			
8	4	31	98	82	83.15	284.8	34.0
9	3	42	108	72	76.73	299.3	68.7
10	2	54	122	58	71.85	309.0	96.3
11	1	62	146	34	67.09	312.8	121.7
Noon		66	180	0	66.00	315.7	128.4

<sup>1</sup> HUTCHINSON, F. W., Solar Irradiation of Walls and Windows Facing South, *Heating, Piping Air Conditioning*, July, 1949, pp. 102-104.<sup>2</sup> Approximates latitude of Wilmington, N.C., Chattanooga, Memphis, Oklahoma City, Albuquerque, Los Angeles.

Table 10-19. Solar Irradiation of Vertical Surfaces Facing South.<sup>1</sup> (Continued)

Latitude 40°

Solar time		Solar altitude	Azimuth	180 - A	Angle of incidence	Btu/hr /sq ft	Instantaneous irradiation, Btu
A.M.	P.M.	H	A	B	i	i <sub>0</sub>	i <sub>0</sub> × cos i
October:							
8	4	15	118	62	63 03	225 0	102 0
9	3	24	131	49	53 18	266 5	159 7
10	2	32	145	35	46 00	284 8	197 8
11	1	37	162	18	40 58	292 5	222 1
Noon		39	180	0	39 00	295 4	229 5
November:							
8	4	9	124	56	56 48	175 9	97 1
9	3	16	136	44	46 25	234 5	162 1
10	2	24	149	31	38 46	269 6	211 1
11	1	28	163	17	32 40	281 4	237 6
Noon		29	180	0	29 00	282 3	246.9
December:							
8	4	9	126	54	54 51	177 9	103 3
9	3	14	136	42	43 86	221 4	159 6
10	2	20	151	29	34 73	260 0	213 7
11	1	24	165	15	28 08	272 8	240 7
Noon		25	180	0	25 04	276 8	250 9
January:							
8	4	9	124	56	56 48	180 0	99 4
9	3	16	136	44	46 25	240 0	166 0
10	2	24	149	31	38 46	276 0	216 1
11	1	28	163	17	32 40	288 0	243 1
Noon		29	180	0	29 00	289.0	252 7
February:							
8	4	15	118	62	63 03	230 3	104 4
9	3	24	131	49	53 18	272 8	163 5
10	2	32	145	35	46 00	291 6	202 5
11	1	37	162	18	40 58	299 5	227 5
Noon		39	180	0	39 00	302 5	235 1
March:							
7	5	9	98	82	82 10	175 9	24 2
8	4	22	110	70	71 51	263 8	83 6
9	3	32	123	57	62 50	288 2	133 1
10	2	41	137	43	56 50	302 9	167 2
11	1	47	157	23	51 13	307 7	193.1
Noon		50	180	0	50.00	309.7	199.1
April:							
6	6	8	81	99			
7	5	19	90	90			
8	4	30	101	79	80 49	280 0	46 2
9	3	41	112	68	73 58	299 3	84 6
10	2	51	128	52	67 20	307 0	119 0
11	1	59	152	28	62 95	310 9	141 4
Noon		61	180	0	61 00	311 8	151 2

<sup>1</sup> HUTCHINSON, F. W., Solar Irradiation of Walls and Windows Facing South, *Heating, Piping Air Conditioning*, July, 1949, pp. 102-104.<sup>2</sup> Approximates latitude of Philadelphia, Columbus, Indianapolis, Denver.

Table 10-19. Solar Irradiation of Vertical Surfaces Facing South.<sup>1</sup> (Continued)

Latitude 48°d

Solar time		Solar altitude	Azimuth	180 - A	Angle of incidence	Btu/hr /sq ft	Instantaneous irradiation, Btu
A.M. *	P.M.	H	A	B	i	i <sub>0</sub>	i <sub>0</sub> × cos i
October:							
8	4	13	119	61	61 81	214 9	101.5
9	3	22	132	48	51 65	263 8	163.7
10	2	27	146	34	42 39	278 4	205 6
11	1	32	163	17	35 82	288 2	233 7
Noon		34	180	0	34 00	291.1	241.3
November:							
8	4	8	125	55	55 39	160 2	91.0
9	3	13	137	43	44 55	214 9	153 1
10	2	17	150	30	34 10	242 3	200 6
11	1	22	164	16	26 96	263 8	235 1
Noon		24	180	0	24 00	269 6	246 3
December:							
8	4	9	127	53	53 53	177 9	105 7
9	3	11	139	41	42 20	192 7	142 7
10	2	13	152	28	30 65	217 5	187 1
11	1	18	165	15	23 26	253 0	232.4
Noon		22	180	0	22 00	266 9	247 5
January:							
8	4	8	125	55	55.39	164 0	93 1
9	3	13	137	43	44 55	220 0	156 8
10	2	17	150	30	34 10	248 0	205 4
11	1	22	164	16	26 96	270 0	240 6
Noon		24	180	0	24.00	276 0	252 1
February:							
8	4	13	119	61	61 81	217 5	102 7
9	3	22	132	48	51 65	266 9	165 6
10	2	27	146	34	42 39	281 7	208 1
11	1	32	163	17	35 82	291 6	236 4
Noon		34	180	0	34.00	294.6	244.2
March:							
7	5	8	101	79	79.11	160 2	30.3
8	4	20	111	69	70.32	256.9	86.5
9	3	29	124	56	60 72	282 3	138 1
10	2	38	140	40	52 90	298 0	179.9
11	1	44	160	20	47.48	307.7	208 0
Noon		45	180	0	45.00	308.7	218.3
April:							
8	4	30	103	77	78 77	280 0	54 5
9	3	39	117	63	69 84	295 4	104.2
10	2	47	133	47	62 29	304 1	141 4
11	1	54	154	26	58 11	309 0	163 2
Noon		56	180	0	56 00	310 9	173.8

<sup>1</sup> HUTCHINSON, F. W., Solar Irradiation of Walls and Windows Facing South, *Heating, Piping Air Conditioning*, July, 1949, pp. 102-104.<sup>d</sup> Approximates latitude of Eastport, Me.; Montreal, Ottawa, Minneapolis, St. Paul, Sheridan, Wyo., Portland, Ore.

given are those existing at the start of the stated hours. (It will be noted that conditions for January and November can be taken as the same, as can those for February and October.)

The solar altitude  $H$  is expressed in degrees of elevation above the true horizon. This is the vertical angle of the sun's rays.

The solar azimuth is expressed in degrees east of north (up to 90 deg for true east) and south of east (up to 180 deg for due south at solar noon); for afternoon hours the azimuth values correspond to the number of degrees west of north.

The angle  $B$  given in the fourth column is 180 deg less the azimuth, hence is equal to the horizontal angle between the direction of the sun's rays and a normal to a south-facing wall.

The angle of incidence  $i$  is the number of degrees between the actual direction of the sun's rays and a normal to the vertical surface. (By trigonometry, the cosine of the angle of incidence is equal to the product of the cosines of its vertical and horizontal component angles,  $H$  and  $B$ .)

The normal intensity  $i_0$  is the Btu received in 1 hr (on a clear day) on 1 sq ft of surface located at sea level and *normal* to the direction of the sun's rays. The evaluation of  $i_0$  depends on the turbidity of the earth's atmosphere, the sun's distance from the earth, and the solar altitude. Turbidity varies with weather and with locality and is indicative of the depletion of solar energy due to the scattering effect of dust and water vapor and the absorption effect of water vapor, carbon dioxide, and ozone. The values shown in these tables will thus not be exact for all localities at all times but are believed to be an approximation of adequate accuracy for most engineering purposes. The shape of the  $i_0$  vs.  $H$  curve is assumed to be fixed, but the magnitude of the  $i_0$  changes as the sun moves closer to or farther from the earth. Maximum values occur in January, when the sun is at a minimum distance from the earth; a decrement of 5 Btu per month has been assumed on either side of January.

The last column of the table is the instantaneous rate of irradiation of unit area of south-facing vertical surface (the product of  $i_0$  and cosine  $i$ ). In using this value, the designer must remember that "irradiation" refers to energy impinging on the surface and is not necessarily indicative either of energy entering the structure through a window or of energy actually absorbed by an opaque wall. The irradiation rate is, however, the basic term for use in evaluating either transmission or absorption.

**Systems for Utilizing Solar Heat.** Solar heating systems usually consist of two interconnected parts: (1) a heat "trap" or accumulator, consisting of double thicknesses of glass separated by an inert air space and backed by black metal heating coils or liquid-containing plate surfaces; and (2) a storage tank, ordinarily merely a well-insulated water-filled tank, of suitable size. The heat trap, designed to admit a maximum amount of heat from the sun and to lose as little as possible by reradiation to the atmosphere, is usually located on the roof and so tilted as to be as nearly normal to the sun's rays as possible.

Tropical regions, such as Miami, have made extensive use of solar radiation, as described above, as a source of service water supply. While there are numerous variations from the simple system, the usual design consists of a glass (preferably double) faced coil some 3 ft or more square, located on the roof or in the back yard, and an oversized well-insulated storage tank in the house. Operation is very satisfactory in normal weather, the insulation being adequate to carry over a relatively short period of bad or sunless weather.

For house heating, an obvious limitation is the size of tank that would be needed for a factor of safety to carry over storms, in any area where heating is really essential. In current experimental installations, Dr. Maria Telkes, research associate at MIT, is attempting to solve this through the use of the heat of fusion of such chemicals as

Glauber's salt. This melts at 90°F, absorbing some 9,500 Btu per cu ft. This heat is thus stored for use when cooled below 90°F such as by passing circulation air over it.

In an experimental house built for Dr. Telkes at Dover, Mass., large panes of figured glass form the front of a blind second story. Black-painted steel sheets are located 3 in. behind the glass. Air blown through the space thus formed absorbs heat from the steel plates for distribution to the house or storage in the salts as required. The Glauber's salt is kept in a large closetlike room in the center of the house in stacked steel canisters. These are permanently sealed, and the salt is thus never exposed to the atmosphere. Air passing over and around the cans gives up or absorbs heat according to the direction of the temperature difference. When heat is needed by the house, air is circulated from the storage room to it. It has not yet been established whether any change or ultimate decomposition of the salts will make replacement necessary.

A second house, on test at MIT, employs conventional water storage in a 1,320-gal attic tank. Thermostatic controls and circulating pumps regulate flow either to the heat trap or to the radiant-coil house-heating system as needed.

A third experimental installation in Switzerland consists of 26,  $1\frac{1}{16}$ -in., 85-ft pipes, having 4-in. centers and a surface of 805 sq ft, located below a double glass roof. A buried 33 cu yd tank serves for storage. The *Engineers' Digest* (British edition, December, 1947) reports that they have been able to heat the tank to the boiling point and that the maximum total actual heat transfer (July) was 800 Btu/sq ft/day as compared with a calculated theoretical maximum of 2,200. This agreed with results at MIT, where the heat trap was reported as about 37 per cent efficient.

It is usually necessary to make some provision to prevent the coils in such systems from freezing and from losing heat to the atmosphere at night and during sunless times.

### THERMAL SPRINGS<sup>1</sup>

In several instances where the temperature of hot springs is adequate, they have been utilized as a source of heat or power.

The outstanding example is the city of Reykjavik, capital of Iceland, where over 3,000 houses receive all heat and hot water from thermal springs located some 15 km distant. In the hot spring region, 43 holes have been bored 4 to 8 in. in diameter and 135 to 720 m in depth. The additive depth of all holes is about 15,000 m. The water temperature at the springs varies from 80 to 90°C (176 to 194°F) with an average of 87°C (189°F). Water flow was originally 100 l per sec, boring increased this to 260 l per sec, and air lift produces a maximum of 300 l per sec. Steel pipe is used as a casing in the uppermost parts of the holes only.

Water flows by gravity to a receiving cistern, thence to a pumping station and the main distribution system. At Reykjavik, seven tanks with total capacity of 7,400 cu m receive the water from the pumps; discharge to the town mains is by gravity from these tanks, with a booster-pump system for maximum needs.

Street mains total 40 km of 1- to 18-in. pipes. Leads from the streets to the houses are mainly  $\frac{3}{4}$  to 1 in.

After considerable experimentation, the following insulation was employed: transmission lines, double cover of a special turf; city mains, porous-lava-slag fill in concrete troughs; outdoor house lines, glass-wool covered with sealed coat of tarred paper; indoor house lines, felt wrapped in linen; receiving cistern, turfy ground; distribution tanks, coated inside with 15 cm of pumice slabs concrete coated; then three layers of asphalted linen; and finally 5 cm of reinforced concrete to protect the linen.

The insulation system has proved so effective that, in the coldest winters, the tem-

<sup>1</sup> SIGURDSSON, HÆLGI, "Hitaveita Reykjavíkur" (Reykjavik Hot Water Supply), Steindorsprent H.F., 1947.



perature drop is only 2 to 3°C from the springs to the distribution tanks (15.3 km), and 3 to 4°C from there to the farthest home on the lines.

As the homes formerly used coal, the hot-water supply lines were merely tapped into the coal boilers, which were left in place to serve as storage tanks. Service water is taken direct from the line before it enters the heating system. Used water is discharged to the sewage system.

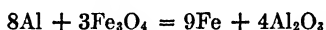
The cost of the project amounted to 30 million króna. The cost of water to the consumer is 0.68 króna per cubic meter from May 14 to Oct. 1, 1.36 króna for the remainder of the year. The savings for the individual consumer compared with the cost of coal amounts to not less than 10 per cent.

Potential locations for similar installations are necessarily limited, such as to California and Wyoming (Yellowstone) in the United States (most other so-called "hot-springs" are warm only), Mexico, Italy, New Zealand, and other volcanic areas, or areas where the earth's crust is thin. However, there are innumerable industrial plants and processes discharging hot water in quantities and at temperatures that would warrant study of the Reykjavik system, with the thought that it might be employed for the use of nearby homes and other buildings.

### THERMIT

Thermit is used extensively as a source of heat where very high sustained temperatures are desired, as in welding heavy sections and in the foundry for purifying iron and steel in the ladle. Three varieties are available, plain thermit consisting of a mixture of iron oxide and aluminum powder; railroad thermit in which  $\frac{5}{8}$  per cent nickel, 1 per cent manganese, and 15 per cent mild steel has been added to plain thermit; and cast-iron thermit in which 3 per cent ferrosilicon and 20 per cent mild steel has been added to plain thermit. The uses of the three types follow their names rather closely.

On ignition, thermit develops temperatures estimated at between 4170 and 4900°F (2300 and 2700°C), with the following chemical reaction:



In nonchemical terms, this means that 217 parts of aluminum unite with 732 parts (both by weight) of iron oxide to form 540 parts of steel and 409 parts of slag.

### ATOMIC ENERGY<sup>1</sup>

Summing up the status of atomic-energy developments, within the limitations necessarily imposed by considerations of national security, David E. Lilienthal, former chairman of the United States Atomic Energy Commission, said on Oct. 6, 1947, with particular reference to the industrial use of atomic power: "... In our opinion the long-time prospects are bright indeed. ... But the fact should be faced squarely that the first commercially practical atomic power plant is **not** just around the corner, not around two corners. ..."

Stressing that a "jungle of difficult scientific and engineering problems" must be penetrated, Lilienthal further stated that "there are other barriers that must be overcome before any substantial part of our energy supply—say 10 to 20 per cent—comes from atomic energy." He noted that the most common estimate or "educated guess" to overcome the technical difficulties and have a useful practical demonstration plant in operation is from 8 to 10 years (from 1947). He felt that it will supplement rather than supplant existing economical sources of energy supply.

<sup>1</sup> "Inter Fuel Competition," Federal Power Commission Report of the Natural Gas Investigation, Part VII, Docket G580, pp. 21–25, February, 1947. THOMAS, C. A., Nonmilitary Uses of Atomic Energy, *Chem. Eng. News*, vol. 24, pp. 2480–2483, Sept. 25, 1946.

**Heat Produced by Nuclear Fission.** Indicating the tremendous potentialities of atomic fission, Gilliland<sup>1</sup> pointed out that 1 lb of uranium when decomposed gives approximately three million times as much heat as would be produced from 1 lb of coal and therefore that 1 lb of uranium is the potential heat equivalent of 1,500 tons of coal, 36 million cu ft of natural gas, or 280,000 gal of oil.

A consideration of fissionable materials and the future development of industrial heat and power from them is of importance as an insight into our energy sources of the future. A group of American scientists in a report to Bernard M. Baruch, United States representative on the United Nations Atomic Energy Commission, released on Sept. 7, 1946, estimated that the operating cost of atomic power would be only 23 per cent more than in a modern public-utility plant using coal costing \$7 a ton. With coal at \$10 a ton the operating costs would be the same. This report was based on studies made under the direction of Dr. Charles A. Thomas, vice-president and technical director of the Monsanto Chemical Co. It was estimated that a nuclear power plant of 75,000 kw capacity could be built and equipped for 25 million dollars and that the operating cost, including 3 per cent interest on the investment, would be 0.80 cent per kilowatt-hour, as compared with a coal plant of the same capacity costing 10 million dollars for installation and 0.65 cent per kilowatt-hour for operation.

While this cost is too high to compete with coal under present conditions, it is reasonable to expect that material lowering of cost will follow from an energetic research program on the industrial utilization of atomic energy.

It is probable that safe and economical central-station power ultimately will be developed on a commercial basis, and it may even prove feasible for driving large ships. Further, it is the belief of many of the scientists connected with this work that a comparatively small nuclear power plant will be developed.

It would appear that the cost of nuclear power may decrease and the cost of coal power increase as time goes by. However, in this connection, it should be noted that the direct and indirect (as reflected in original plant costs) labor and supervision costs for the nuclear plant are expected to be greater than for the coal plant, an item which might offset increasing costs of coal fuel.

The nuclear power plant offers an attractive combination with the modern gas turbine, obviating the need for large cooling-water supplies, and virtually eliminating both the transportation and storage of coal or other bulk fuels.

In addition to the question of nuclear power vs. solid, liquid, or gaseous fuels, the nuclear power plant has advantages and fields of application not open to other types of power-producing plants.

Aside from the highly important and extremely complex problems of safety, details which must be solved before nuclear power can be offered commercially include the probable use of very high temperatures in the nuclear plant; the effect of radiation on the various materials or parts necessary to plant construction; the purification of coolants and waste products; extraction of the "ash" or spent fuel and insertion of fresh nuclear material without interrupting operation; developing a means of either servicing the device or making it absolutely service-free, and the necessity for working in an entirely virgin field of engineering where even the most basic information on the physical and chemical properties under the essential conditions of operation are lacking.

**Reserves.** Information is not available on the national reserves of fissionable material such as uranium and thorium. On the basis of 1,600 tons of coal being equivalent to 1 lb of fissionable material (uranium products), only about 1 million tons of the latter would be required to equal the entire estimated (high) national reserve of 3.2 trillion tons of coal.

<sup>1</sup> GILLILAND, E. R., deputy dean of engineering, MIT.



## **SECTION 3**

### **COMBUSTION**



## CHAPTER 11

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### THE COMBUSTION OF FUELS

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## THE FUNDAMENTAL REACTIONS OF COMBUSTION

Combustion may be defined as any chemical process accompanied by the evolution of light and heat, commonly the union of substances with oxygen. Where the reaction is slower and not accompanied by light, it is usually known as oxidation, even though the combustion reaction is the same. The difference between combustion and oxidation is thus often a matter of speed of reaction only. Nitrogen, and the very small amounts of other gases commonly present in air, do not enter into the combustion processes, since, to all practical purposes, they are inert. In fact, the presence of nitrogen actually lowers the flame temperature by the amount required to heat the nitrogen.

### Elements of Combustion<sup>1</sup>

Of all the chemical elements, only carbon, hydrogen, and sulphur are combustibles, in the sense of commercial combustion problems. Oxygen is not combustible but will support the combustion of these three. Nitrogen is inert, being neither combustible nor a supporter of combustion.

All the compounds of commercial combustion are combinations of some two of the four elements carbon, hydrogen, oxygen, and sulphur. Of these, the following are the compounds formed in normal furnace reactions:

1. **Carbon dioxide:** the complete union of carbon and oxygen
2. **Carbon monoxide:** the partial combustion of carbon and oxygen, such as with a restricted supply
3. **Sulphur dioxide:** the partial, though normal, union of sulphur and oxygen
4. **Sulphur trioxide:** the complete union of sulphur and oxygen, but requiring a more complex condition for its formation in appreciable quantities.

**Computation of Weights of Products of Combustion.** The usual method consists in obtaining the molecular weights of the components of the equation at hand (such as from Table 11-2, second column) and substituting these values in the equation to be solved.

**Example.** To find the weights of the product formed in burning carbon to carbon dioxide ( $\text{CO}_2$ ), find from Table 11-1 that the equation is  $\text{C} + \text{O}_2 = \text{CO}_2$ ; and from Table 11-2 that the respective molecular weights of carbon and oxygen are 12 and 32. Then, since the formula  $\text{C} + \text{O}_2$  call for one molecule (or mol) each of carbon and oxygen, it follows that 12 lb of carbon will unite with 32 lb of oxygen to form 44 lb of carbon dioxide. (Similar calculations for other products are shown as the last column of Table 11-1.)

**Addition of Nitrogen Weight.** Since oxygen is seldom used in a pure state, but as mixed with nitrogen in air, it is necessary to add the nitrogen weight accompanying the oxygen used, to obtain the total resultant carbon dioxide plus the nitrogen. This is the true total weight of the product of complete combustion of pure carbon.

**Example.** From Table 11-3 it is seen that for every pound of oxygen used, 3.32 lb of nitrogen will be carried along as an inert. Thus, in our example, the 32 lb of oxygen needed for making 44 lb of  $\text{CO}_2$ , will contain  $32 \times 3.32$  or 106.24 lb of nitrogen to raise the total product weight to  $44 + 106.24$ , or 150.24 lb.

As the ratios of the elements are constant, it is merely a matter of mathematics to convert such calculations to terms of one or any given number of pounds of fuel.

<sup>1</sup> SWAIN, P. W., and L. N. ROWLEY, "Library of Practical Power Engineering" (collection of articles published in *Power*), Part II, Chap. 7, pp. 4-6, McGraw-Hill Publishing Company, Inc., New York, 1949.

Table 11-1. Chemical Reactions

Combustible substance	Reaction	Mols	Lb <sup>a</sup>
Carbon to carbon monoxide.	$C + \frac{1}{2}O_2 = CO$	$1 + \frac{1}{2} = 1$	$12 + 16 = 28$
Carbon to carbon dioxide	$C + O_2 = CO_2$	$1 + 1 = 1$	$12 + 32 = 44$
Carbon monoxide to carbon dioxide. . . . .	$CO + \frac{1}{2}O_2 = CO_2$	$1 + \frac{1}{2} = 1$	$28 + 16 = 44$
Hydrogen . . . . .	$H_2 + \frac{1}{2}O_2 = H_2O$	$1 + \frac{1}{2} = 1$	$2 + 16 = 18$
Sulphur to sulphur dioxide	$S + O_2 = SO_2$	$1 + 1 = 1$	$32 + 32 = 64$
Sulphur to sulphur trioxide	$S + \frac{3}{2}O_2 = SO_3$	$1 + \frac{3}{2} = 1$	$32 + 48 = 80$
Methane. . . . .	$CH_4 + 2O_2 = CO_2 + 2H_2O$	$1 + 2 = 1 + 2$	$16 + 64 = 44 + 36$
Ethane . . . . .	$C_2H_6 + \frac{7}{2}O_2 = 2CO_2 + 3H_2O$	$1 + \frac{7}{2} = 2 + 3$	$30 + 112 = 88 + 54$
Propane. . . . .	$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$	$1 + 5 = 3 + 4$	$44 + 160 = 132 + 72$
Butane . . . . .	$C_4H_{10} + \frac{13}{2}O_2 = 4CO_2 + 5H_2O$	$1 + \frac{13}{2} = 4 + 5$	$58 + 208 = 176 + 90$
Acetylene. . . . .	$C_2H_2 + \frac{5}{2}O_2 = 2CO_2 + H_2O$	$1 + \frac{5}{2} = 2 + 1$	$26 + 80 = 88 + 18$
Ethylene. . . . .	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$	$1 + 3 = 2 + 2$	$28 + 96 = 88 + 36$

<sup>a</sup> Substitute the molecular weights in the reaction equation to secure pounds. The pounds on each side of the equation must balance.

Table 11-2. Properties of Combustion Elements<sup>1</sup>

Element or compound	Formula	Mol. wt	At 14.7 psia, 60°F		Nature		Heat value, Btu		
			Wt, lb/cu ft	Vol, cu ft/lb	Gas or solid	Combustible	Per lb	Per cu ft at 14.7 psia, 60°F	Per mol
Carbon.	C	12			S	Yes	14,540	.....	174,500
Hydrogen	H <sub>2</sub>	2.02 <sup>a</sup>	0.0053	188	G	Yes	61,000	325	123,100
Sulphur . .	S	32			S	Yes	4,050	.....	129,600
Carbon monoxide	CO	28	0.0739	13.54	G	Yes	4,380	323	122,400
Methane	CH <sub>4</sub>	16	0.0423	23.69	G	Yes	24,000	1,012	384,000
Acetylene	C <sub>2</sub> H <sub>2</sub>	26	0.0686	14.58	G	Yes	21,500	1,483	562,000
Ethylene	C <sub>2</sub> H <sub>4</sub>	28	0.0739	13.54	G	Yes	22,200	1,641	622,400
Ethane	C <sub>2</sub> H <sub>6</sub>	30	0.0792	12.63	G	Yes	22,300	1,762	668,300
Oxygen . .	O <sub>2</sub>	32	0.0844	11.84	G				
Nitrogen . .	N <sub>2</sub>	28	0.0739	13.52	G				
Air <sup>b</sup> . . . .	.....	29	0.0765	13.07	G				
Carbon dioxide. .	CO <sub>2</sub>	44	0.1161	8.61	G				
Water	H <sub>2</sub> O	18	0.0475	21.06	G				

<sup>1</sup> SWAIN, P. W., and L. N. ROWLEY, "Library of Practical Power Engineering" (collection of articles published in *Power*), Part II, p. 9, McGraw-Hill Publishing Co., Inc., 1949.

<sup>a</sup> For most practical purposes, the value of 2 is sufficient.

<sup>b</sup> The molecular weight of 29 is merely the weighted average of the molecular weight of the constituents.

Table 11-3. Composition of Atmospheric Air

	By volume		By weight	
	Per cent	Ratio	Per cent	Ratio
Nitrogen.....	79	3.76	76.8	3.32
Oxygen.....	21	1.00	23.2	1.00
Total . . . . .	100	4.76	100.0	4.32



CALCULATION OF GAS VOLUMES<sup>1</sup>

All the basic chemistry of the preceding section was in terms of weights. A knowledge of volume relations is also important because all the combustion products and many combustibles are gases.

There are three basic laws of gases, all important, those of Charles, Boyle, and Avogadro.

**Charles's Law:** If a given weight of gas is kept at constant pressure, its volume will be proportional to its absolute temperature.

Thus, if the absolute temperature is doubled, the volume will be doubled (absolute temperature = °F + 460).

**Example.** Given 400 cu ft of gas at 60°F. To compute the new volume if the temperature is raised to 600°F without change in pressure.

**Answer.** Original absolute temperature = 60 + 460, or 520°. Final absolute temperature = 600 + 460, or 1060. Ratio of volumes is thus  $1060 \div 520 = 2.04$ , so final volume is  $2.04 \times 400$  or 816 cu ft.

**Boyle's Law:** If a given weight of gas is kept at constant temperature, its volume will be inversely proportional to the absolute pressure.

Thus, if the pressure is doubled, without change in temperature, the volume will be halved (absolute pressure is gauge pressure plus 14.7 psi at standard sea-level barometric pressure).

**Example.** Given 400 cu ft of gas at 10 lb gauge. To compute the volume at 80 lb gauge without change in temperature.

**Answer.** Original absolute pressure 10 + 14.7 or 24.7 psia. Final absolute pressure 80 + 14.7, or 94.7. Then ratio is  $94.7 \div 24.7$ , or 3.83 and final volume is  $400 \div 3.83$ , or 153.2 cu ft.

Avogadro's law is almost as useful as Charles's and Boyle's, but less widely understood:

**Avogadro's Law (Statement 1):** At given pressure and temperature, all gases have the same number of molecules per cubic foot.

**Avogadro's Law (Statement 2):** At given pressure and temperature, the weight of 1 cu ft of any gas is directly proportional to its molecular weight.

Statement 2 follows directly from statement 1. If the volume is properly selected, the number expressing the actual weight in pounds will be the same number as that expressing the molecular weight. For standard conditions (60°F and 14.7 lb abs), this volume will be 379 cu ft.

**The "Mol."** This quantity of any gas, whether expressed in pounds or as 379 cu ft at standard conditions, is called one "pound-mol" or, for short, simply one "mol."

Thus a mol of hydrogen is 2 lb of hydrogen (since the molecular weight of H<sub>2</sub> is 2). Likewise a mol of oxygen (O<sub>2</sub>) is 32 lb, and so on for all gases.

**NOTE:** The *weight* of a mol is not affected by changes in pressure and temperature, but the *volume* does change. Thus, at 32°F and 14.7 psia the volume of a mol is 359 cu ft.

By simple algebra, the laws of Charles, Boyle, and Avogadro can be combined into a simple formula relating pressure, volume, and temperature for any gas. By means of this formula and molecular weights, all gas volumes and weights can be figured entirely without tables. The formula follows:

$$PV = KT$$

where  $K = 10.7 \div$  molecular weight

$P$  = absolute pressure, psi

$V$  = volume of 1 lb of the given gas, cu ft

$T$  = absolute temperature

<sup>1</sup> SWAIN, P. W., and L. N. ROWLEY, *loc. cit.*

For convenience, this formula can be written in the following three ways:

$$\text{Pressure} = K \times \text{temperature} \div \text{volume} \quad (1)$$

$$\text{Volume} = K \times \text{temperature} \div \text{pressure} \quad (2)$$

$$\text{Temperature} = \text{pressure} \times \text{volume} \div K \quad (3)$$

NOTE: In all the foregoing, the temperatures and pressures used must be *absolute*.

**Problem.** Without referring to any tables, find the volume of 1 lb of nitrogen at atmospheric pressure and 60°F.

**Solution.** Pressure = 14.7 psia absolute temperature = 60 + 460 = 520°. For nitrogen  $K = 10.7 \div 28 = 0.382$ . Thus volume =  $0.382 \times 520 \div 14.7$  or 13.5 cu ft.

Since the above problem was figured for standard pressure and temperature, the volume of 1 mol can be checked, by multiplying by 28 (molecular weight of nitrogen); thus  $28 \times 13.5 = 379$  cu ft (checks).

Two more convenient formulas follow:

At 60°F and 14.7 psia,

$$\text{Volume of 1 lb of gas} = 379 \div \text{molecular weight}$$

$$\text{Weight of 1 cu ft of gas} = \text{molecular weight} \div 379$$

Table 11-1 shows all the more common combustion reactions in terms of volumes. Volume of each gaseous substance is directly proportional to the number of molecules

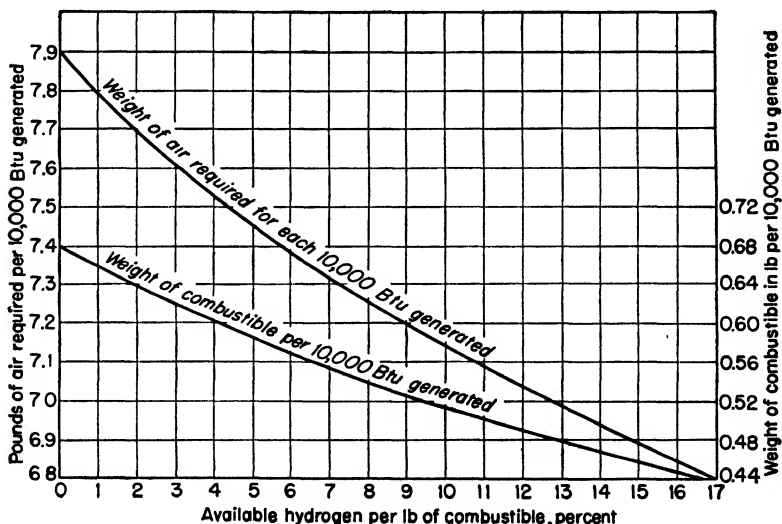
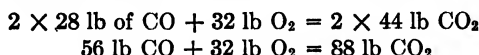


FIG. 11-1. Theoretical air required and combustible per 10,000 heat units (Btu). (Cochrane Corp., Philadelphia, 1928.)

in the equation. Thus two molecules of CO combine with one molecule of  $O_2$  to produce two molecules of  $CO_2$ . Also two volumes of CO combine with one volume of  $O_2$  to make two volumes of  $CO_2$ . Also (since the mol is a unit of volume, 379 cu ft under standard conditions) 2 mols of CO combine with 1 mol of  $O_2$  to make 2 mols of  $CO_2$ . Finally, mols can be readily converted back to pounds, thus:



Clearly, the mol is extremely convenient in figuring combustion problems involving

Table 11-4. Air Required for and Products of Combustion<sup>1</sup>

(Gives required combustion air and products for common combustibles burned with theoretical air requirements. Air and products are given in mols, cubic feet, and pounds (for 1 mol, 1 cu ft, and 1 lb of fuel)

Fuel	For 1 mol of fuel					For 1 cu ft of fuel					For 1 lb of fuel				
	Air		Other products (than N <sub>2</sub> )			Air		Other products (than N <sub>2</sub> )			Air		Other products (than N <sub>2</sub> )		
	O <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	SO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	SO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	SO <sub>2</sub>
C:															
Mols	1 0	3 76	1 0	...	...	...	...	...	...	...	0 0833	0 313	0 0833	...	...
Cu ft	379	1,425	379	...	...	...	...	...	...	...	31 6	118 8	31 6	...	...
Lb	32 0	105	44.0	...	...	...	...	...	...	...	2 67	8 78	3.67	...	...
H <sub>2</sub> :															
Mols	0 5	1 88	...	...	...	...	...	...	...	...	0 250	0 940	...	0.5	...
Cu ft	189 5	712	...	...	...	...	...	...	...	...	94 8	356	...	...	...
Lb	16 0	25.6	...	...	...	...	...	...	...	...	8 0	26 3	...	...	...
S:															
Mols	1 0	3 76	...	...	1 0	...	...	...	...	...	0 0312	0 1176	...	9 0	0.0312
Cu ft	379	1,425	...	...	379	...	...	...	...	...	11 84	44 6	...	...	11 84
Lb	32 0	105	...	...	64	...	...	...	...	...	1 0	3 29	...	...	2 0
CO:															
Mols	0 5	1 88	1 0	...	...	0 00132	0 00196	0 00264	...	...	0 179	0 0672	0 0357	...	...
Cu ft	189 5	712	379	...	...	0 5	1 88	1 0	...	...	6 77	25 4	13 53	...	...
Lb	16 0	52 6	44 0	...	...	0 0422	0 139	0 116	...	...	0 571	1 88	1 57	...	...
CH <sub>4</sub> :															
Mols	2 0	7 52	1 0	2 0	...	0 00528	0 0198	0 00264	0 00528	...	0 125	0 470	0 0625	0.125	...
Cu ft	758	2,850	379	...	...	2 0	7 52	1 0	...	...	47 4	178	23 7	...	...
Lb	64 0	210	44 0	36 0	...	0 169	0 556	0 116	0 0950	...	4 0	13 17	2 75	2 25	...
C <sub>2</sub> H <sub>6</sub> :															
Mols	2 5	9 40	2 0	1 0	...	0 0066	0 0248	0 00528	0 00264	...	0 0962	0 362	0 0769	0.0385	...
Cu ft	947	3,560	758	...	...	2 5	9 40	2 0	...	...	36 4	137	29 15	...	...
Lb	80 0	263	88 0	18 0	...	0 211	0 694	0 232	0 0475	...	3 08	10 13	3 38	0 692	...
C <sub>3</sub> H <sub>8</sub> :															
Mols	3 0	11 29	2 0	2 0	...	0 00792	0 0238	0 00528	0 00528	...	0 1071	0 403	0 0714	0 0714	...
Cu ft	1,137	4,280	758	...	...	3 0	11 29	2 0	...	...	40 6	153	27 1	...	...
Lb	96 0	316	88 0	36 0	...	0 253	0 834	0 232	0 0950	...	3 43	11 29	3 14	1-286	...
C <sub>4</sub> H <sub>10</sub> :															
Mols	3 5	13 17	2 0	3 0	...	0 00923	0 0347	0 00528	0 0079	...	0 1167	0 439	0 0667	0.10	...
Cu ft	1,326	4,990	758	...	...	3 5	13 17	2 0	...	...	44 2	166 3	25 3	...	...
Lb	112 0	369	88 0	54 0	...	0 296	0 972	0 232	0 1425	...	3 73	12 29	2 93	1.8	...

<sup>1</sup>Power, December, 1948, p. 118.

<sup>a</sup> Varying assumptions for molecular weight introduce a slight inconsistency in the values of air and combustion products from the burning of hydrogen. True molecular weight of hydrogen is 2.02, but the approximate value of 2 is used in figuring the air and combustion products.

Table 11-5. Properties and Data on Components and Products of Combustion

	Molecular symbol	Atomic weight	Mol. wt	Ignition temp, deg F	Relative density		Wt, lb/cu ft	Vol, cu ft/lb	$R^a$	Btu		Mean Specific heat <sup>b</sup>
					air = 1	H <sub>2</sub> = 1				Higher	Lower (net)	
Carbon . . . . .	C <sup>c</sup>	12 008		<sup>d</sup>	0 820 <sup>e</sup>		0 0668 <sup>f</sup>	14 97 <sup>g</sup>		14 540/ <sup>h</sup>		
Hydrogen . . . . .	H <sub>2</sub>	1 008	2 015	1130	0 0696	1	0 00562	177 906	765 8	62 000	52 920	3 4750
Oxygen . . . . .	O <sub>2</sub>	16 000	32 000	<sup>g</sup>	1 1053	16	0 08921	11 209	48 24	<sup>g</sup>	<sup>g</sup>	0 2211
Sulphur . . . . .	S <sub>2</sub>	32 07	64 14	470								
Nitrogen . . . . .	N <sub>2</sub>	14 01	28 02		0 9673	14	0 07807	12 809	55 13	5 940 <sup>h</sup>		0 2406
Carbon dioxide . . . . .	CO <sub>2</sub>		44 01	<sup>g</sup>	1 5291	22	0 12341	8 103	34 88	<sup>g</sup>		0 2214
Carbon monoxide . . . . .	CO		28 01	1210	0 9672	14	0 07806	12 811	55 15	4 380		0 2406
Methane . . . . .	CH <sub>4</sub>		16 03	1202	0 5576	8	0 04500	22 222	95 64	23 850	21 670	0 649
Acetylene . . . . .	C <sub>2</sub> H <sub>2</sub>		26 03	900	0 9200	13	0 7425	13 468	57 97	21 460	20 420	
Ethylene . . . . .	C <sub>2</sub> H <sub>4</sub>		28 03	1022	0 9674	14	0 07808	12 807	55 12	21 450		0 461
Ethane . . . . .	C <sub>2</sub> H <sub>6</sub>		30 05	1000	1 0494	15	0 08470	11 806	50 81	22 230	20 500	
Sulphur dioxide . . . . .	SO <sub>2</sub>		64 07		2 2639	32	0 18272	5 473	23 56			
Air . . . . .			28 94		1 0000	14 5	0 08071	12 390	53 33			

<sup>a</sup>  $R$  in  $PV = RT$  formula.<sup>b</sup> 0 to 600°F at 32°F and atmospheric pressure.<sup>c</sup> Atomic symbols.<sup>d</sup> Ignition temperature of fixed carbon: bituminous coal 766°F (approximately); anthracite 925°F (approximately).<sup>e</sup> If carbon can be conceived to exist as a gas under standard conditions, its relative density, weight, and volume would be as shown.<sup>f</sup> 14,540 is as burned to CO<sub>2</sub>; carbon burned to CO is 4,380 Btu.<sup>g</sup> Nonflammable.<sup>h</sup> Value shown is as burned to SO<sub>2</sub>; sulphur to SO<sub>3</sub> is 4,050 Btu.

the analysis of flue gases or of fuel gases, as it is possible to work in either volumes or weights and to change back and forth quickly.

Note that the weight of 1 mol of  $\text{CO}_2$  is always 44 lb, regardless of pressure or temperature. Its volume is 379 cu ft at standard conditions, also 359 cu ft at 14.7 psia and  $32^\circ\text{F}$ .

*Mols of Solids (Carbon and Sulphur).* A mol of carbon is 12 lb and a mol of sulphur 32 lb. Obviously, however, a mol of carbon at standard pressure is not 379 cu ft, because it is not a gas. In the case of carbon and sulphur, therefore, consider the *weight* of the mol, but not the volume.

*Mols of Water.* Water is a joker in a mol analysis. Water vapor is a gas, an imperfect gas that follows the gas-volume formula roughly at high temperatures. When flue gas is analyzed, the water vapor condenses to a liquid so that none of its volume shows up in the analysis.

### REQUISITES TO PROPER COMBUSTION

In view of the great number of factors involved in the combustion of any fuel, and the great variation in the characteristics not only of different classes of fuel, but of different fuels of the same class, it is obvious that the specific requirements for the proper combustion of an individual fuel must be considered as a distinct problem. It is possible, however, from the foregoing, to draw certain general conclusions as to the combustion requirements of any fuel, whether solid, liquid, or gaseous; and, since such conclusions form the basis of the design of all combustion apparatus, they are worthy of careful note.

These general requirements of proper combustion may be summarized as follows:

1. The **admission of an air supply** such as will assure sufficient oxygen for complete combustion.
2. Since complete combustion is not of necessity efficient combustion, it must be secured **without** permitting the **dilution of the products of combustion** with excess air. It follows then, that
3. The air supply should be admitted at the **proper time and in such a manner** that the oxygen of the air comes into free and intimate contact with the combustible substances of the fuel. In the case of solid fuels, this means not only into contact with the solid particles of the oxidizable substances, but also with the combustible gases as they are distilled from the fuel.
4. The gases must be **maintained at a temperature** at or above their ignition point until combustion is complete. Theoretically, as has been indicated, the most efficient combustion is that resulting in the maximum temperature possible. In practice, there are frequently factors which, from the standpoint of practical operating efficiency, make it advisable to keep furnace temperatures somewhat below those which could be obtained were this the sole factor involved.
5. An additional requirement, which has to do with the physical rather than the chemical aspect of combustion, is that **proper provision** must be made for the **expansion of gases** during the period of their combustion.

In considering combustion, it is necessary, though perhaps difficult for the average boiler user, to distinguish between the purely chemical changes that accompany oxidization and the purely physical aspect of the later transformation of heat energy in the passage of the products of combustion through the boiler, *i.e.*, the absorption of heat by the boiler from such gases. The efficiency of combustion is thus independent of the ability of the boiler under which combustion takes place to absorb heat, and in the requirements of proper combustion just summarized such ability is either assumed or neglected.

From the general conclusions drawn, it would seem perhaps a simple matter to

meet the requirements of proper combustion. Unfortunately, however, such is not the case, and it is, as stated heretofore, the physical and mechanical details encountered in attempting to fulfill such requirements that render the problem of proper combustion difficult. Assuming proper furnace form and adequate combustion temperatures, the problem is solely one of air admission and admixture. The factors entering into the problem and the methods used to bring about the desired results are so widely varied for different fuels that it is necessary, as stated, to consider each class of fuel specifically for any but the most general statements.

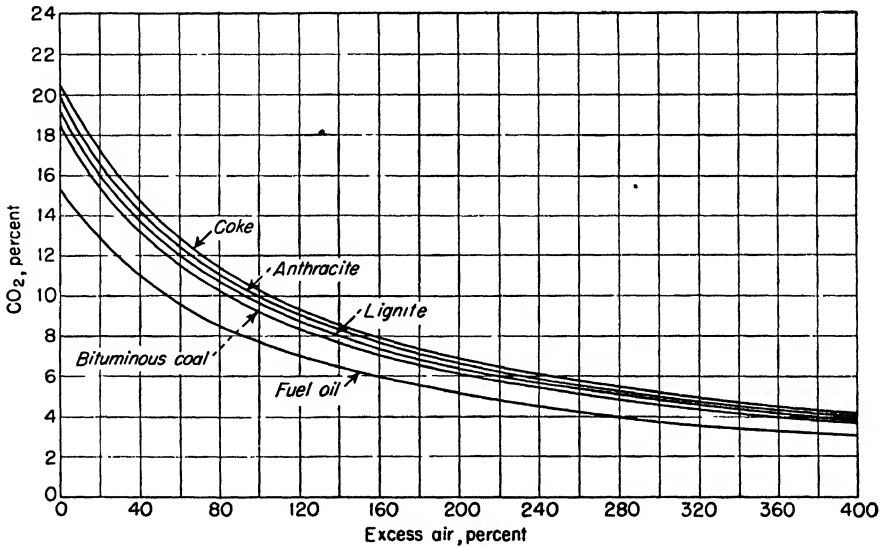


FIG. 11-2. Relationship of CO<sub>2</sub> and excess air per cent for solid fuels and fuel oil.

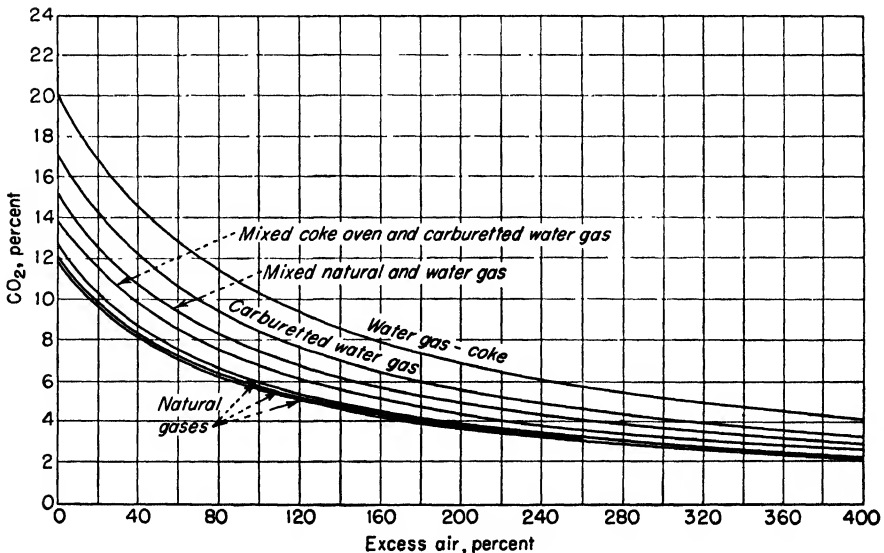


FIG. 11-3. Relationship of CO<sub>2</sub> and excess air per cent for gases shown.

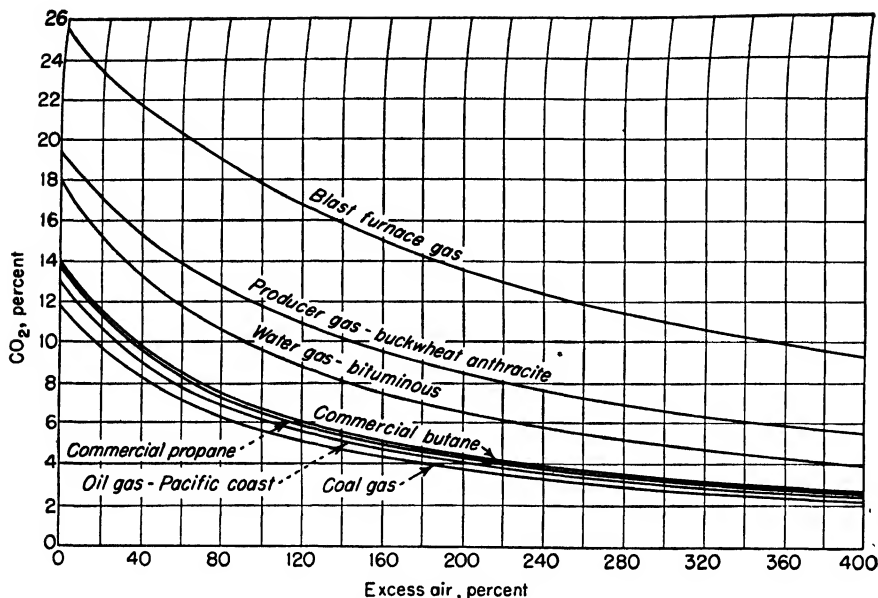


FIG. 11-4 Relationship of  $\text{CO}_2$  and excess air per cent for gases shown.

### Furnace Atmospheres<sup>1</sup>

**Oxidizing atmosphere** in a furnace means an atmosphere in which there is an excess of oxygen or air present. Sometimes it is desired to have such an atmosphere to aid certain chemical reactions. In most cases of furnace heating, this type of atmosphere results in waste of fuel and, in processing, in scaling of the work. Also, in some cases, an oxidizing atmosphere exists because it has been necessary to reduce the flame temperature by dilution with cold air for low-temperature operations.

**Reducing atmosphere** in a furnace means an atmosphere in which there is a deficiency of oxygen or air to complete the process of combustion. Such an atmosphere is deliberately produced in some operations to aid certain chemical reactions or to preclude scaling or oxidizing of the work. In most cases of furnace heating, excessive reducing atmosphere causes a waste of unconsumed fuel and a lowering of furnace temperatures.

**Neutral atmosphere** is, as the name suggests, neither oxidizing nor reducing and indicates a state of perfect combustion. For a given high-temperature heating furnace, this type of atmosphere is usually the ideal and represents maximum fuel economy in combustion.

### RATE OF COMBUSTION VS. AIR SUPPLIED<sup>2</sup>

(Solid Fuels)

The popular conception that "the more air that is supplied, the more rapid the rate of combustion of solid fuels" is most definitely incorrect for underfeed firing and subject to important limitations for overfeed (such as hand-firing) firing. Nicholls<sup>2</sup> and others have shown that the mechanism of the relation between air supplied and rate of combustion is quite complex and subject to very definite restraining limits.

<sup>1</sup> "Hauck Industrial Combustion Data," p. 6, Hauck Mfg. Co., Brooklyn, New York, 1944.

<sup>2</sup> NICHOLLS, P., "Underfeed Combustion, Effect of Preheat, and Distribution of Ash in Fuel Beds," U.S. Bur. Mines Bull. 378, 1934.

Table 11-6. Maximum CO<sub>2</sub> and Air Required for Combustion<sup>1</sup>

Fuel	No. of samples	Combustion conditions at zero excess air			
		Atmospheric air required (lb/10,000 Btu)		Max CO <sub>2</sub> per cent	
		Range	Avg	Range	Avg
Anthracite:					
New Mexico.....	1	.....	7.83	.....	19.5
Colorado.....	1	.....	7.85	.....	19.3
Pennsylvania.....	3	7.81-7.93	6.87	20.0-20.0	20.0
Semianthracite.....	3	7.68-7.82	7.74	19.1-19.2	19.1
Bituminous coal:					
Low-volatile .. . . .	5	7.62-7.76	7.69	18.5-18.9	18.7
Medium-volatile .. .	1	.....	7.77	.....	18.5
High-volatile A .. .	15	7.51-7.73	7.63	17.7-18.7	18.4
High-volatile B .. .	5	7.56-7.73	7.66	18.0-18.7	18.4
High-volatile C .. .	4	7.54-7.67	7.60	18.0-18.5	18.2
Subbituminous coal ..	2	7.56-7.57	7.56	19.1-19.2	19.1
Lignite:					
North Dakota .. . .	1	.....	7.47	.....	19.5
Texas.....	1	.....	7.52	.....	19.2
Coke:					
High-temperature .. .	1	.....	7.96	.....	20.7
Low-temperature .. .	1	.....	7.63	.....	19.3
Beehive .. . . .	1	.....	8.05	.....	20.5
By-product .. . . .	1	.....	8.01	.....	20.5
Gasworks coke .. . .	3	8.02-8.10	8.06	20.4-20.6	20.6
Petroleum coke.. ..	1	.....	7.73	.....	19.5
Pitch coke .. . . .	1	.....	8.13	.....	20.7
Wood: <sup>a</sup>					
Softwoods... .. .	8	7.02-7.22	7.11	18.7-20.4	19.8
Hardwoods .. . . .	10	7.09-7.28	7.15	19.5-20.5	20.0
Bagasse .. . . .	6	6.25-6.99	6.59	19.4-20.5	20.3
Petroleum oils:					
Gasoline (60°API) ..	1	.....	7.46	.....	14.9
Kerosene (45°API) ..	1	.....	7.42	.....	15.1
Gas oil (30°API) .. .	1	.....	7.45	.....	15.5
Fuel oil (15°API).. .	1	.....	7.58	.....	15.9
Gaseous fuels:					
Natural gas .. . . .	7	7.32-7.41	7.37	6.9-15.2	12.2
Refinery and oil gas ..	8	6.52-7.38	7.14	10.7-13.6	12.8
Blast-furnace gas .. .	6	5.73-6.27	5.82	20.0-26.9	24.7
Coke-oven gas .. . .	6	6.66-7.02	6.80	9.5-12.7	11.1
Carbureted water gas ..	1	.....	.....	.....	17.2 <sup>b</sup>
Producer gas:					
Anthracite .. . . .	1	.....	.....	.....	19.4 <sup>b</sup>
Bituminous coal .. .	1	.....	.....	.....	18.9 <sup>b</sup>
Coke .. . . .	1	.....	.....	.....	20.5 <sup>b</sup>
Retort coal gas .. . .	1	.....	.....	.....	11.9 <sup>b</sup>
Water gas, coke .. . .	1	.....	.....	.....	20.1 <sup>b</sup>
Water gas, bituminous.	1	.....	.....	.....	18.0 <sup>b</sup>
Propane.....	1	.....	7.24	.....	13.7 <sup>c</sup>
Butane .. . . .	1	.....	7.26	.....	14.0 <sup>c</sup>
Methane .. . . .	1	.....	7.20	.....	11.7 <sup>c</sup>

<sup>1</sup> "Combustion Engineering," pp. 25-3 to 25-13, Combustion Engineering-Superheater Corp., 1947 (except as noted in footnotes b and c).

<sup>a</sup> Calculated from higher heating value of kiln-dried wood at 8 per cent moisture.

<sup>b</sup> "Gaseous Fuels," pp. 284-285, AGA, New York, 1948.

<sup>c</sup> "Handbook Butane-Propane Gases," p. 32, Western Business Papers.



## Underfeed Firing

For underfeed firing, this is best illustrated by Fig. 11-5, which is a plot of the primary air supplied against combustible (moisture- and ash-free fuel) burned per hour. This particular curve, used for illustration of the principle, is for 1- by 1½-in. high-temperature coke. Curves for other fuels and fuel sizes follow.

The two main plots are the rate of ignition (*cbd*) and the rate of burning of combustible (*abd*). Following the rate of ignition from low to high air supply (left to right on *cbd*), it will be seen that at *c* the rate of ignition greatly exceeds the rate of burning. Under these conditions, the thickness of the burning zone would increase continually until the entire fuel bed was involved. At *b* the rate of ignition and the rate of burning are equal, merging the curves, and placing the fire in equilibrium. By equilibrium is meant that, as the rate of ignition and rate of burning are now equal, the depth of the actual active fire zone will remain constant. Beyond *b* (*b* to *d*), the rates of ignition and burning are the same, but the rate of combustion, as indicated by

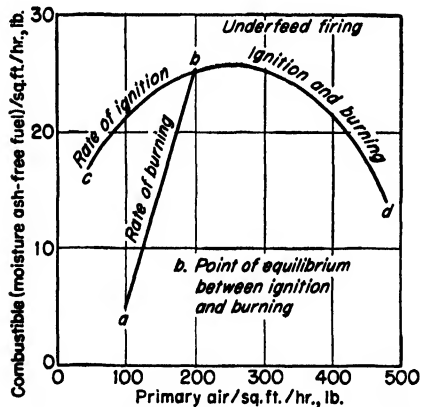


FIG. 11-5. Relation between combustion and air supplied (1½- by 1-in. high-temperature coke). (U.S. Bureau of Mines, Bull. 378.)

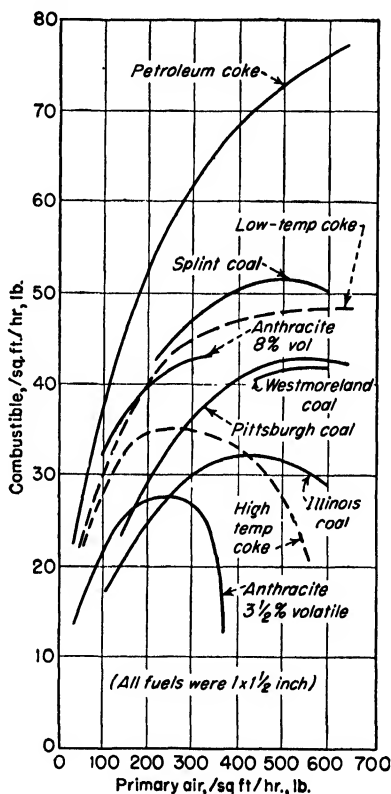


FIG. 11-6. Rate of ignition of various fuels vs. primary air supplied (all at 1-by 1½-in. size). (P. Nicholls, U.S. Bureau of Mines.)

the left-hand scale, drops as the amount of primary air supplied exceeds, by more and more, the optimum rate at which the fire zone can absorb primary air.

For anthracite (Fig. 11-5), this falling off of the rate of combustion as the air supply passes the point of equilibrium is very rapid, to indicate a very critical air-fuel relationship. For bituminous coal (Fig. 11-6) the drop in combustion rate is relatively small, indicating less critical conditions. High-temperature coke drops at a rate midway between anthracite and coke (Fig. 11-6).

Beyond point *d* in Fig. 11-5 and the end of the curve in all similar figures, the air supply so exceeds the rate at which the fuel bed can absorb it that the air literally blows the fire out to make ignition impossible.

The highly significant facts shown by these curves are that the **rate of burning with each rate of air supply must follow curve abd**, and that the **maximum rate of burning with any air supply cannot exceed the peak of curve abd**. No manipulation other than changing the area of the plane of ignition can make the rate of burning continuously exceed the values fixed by the curve. For example, the maximum rate of burning possible with this coke and this particular size is about 26 lb of combustible (or 29 lb of coke) per sq ft per hr, and no manipulation can increase it.

**Effect of Fuel Size on Combustion-Air Ratio.** Having shown the general interpretation of combustion-air ratio curves, Fig. 11-6 shows the rate-of-ignition and rate-of-burning curves for four different sizes of coke.

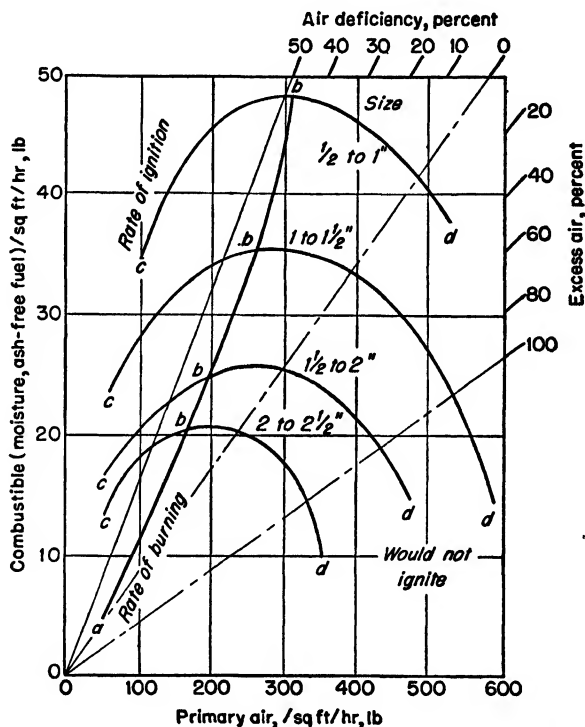


FIG. 11-7. Relation between combustion and air supply for various sizes of high-temperature coke.

It is of interest that the rate-of-burning curves, before their intersection with their individual rate-of-ignition curves, all fall on a common curve (*ab*) which bends but slightly upward for smaller sizes.

The figure shows that the rate of ignition increases rapidly with decrease in size, which agrees with common experience. The relationship, based on the points of intersection of the ignition and burning curves, is of the order shown by Fig. 11-7.

It will be noted that the maximum rates of burning that can be attained are very much affected by the size of the pieces. With the 2- to 2½-in. size, the maximum rate of burning possible under any underfeed conditions was 21 lb, whereas with the ½- to 1-in. size it was 48 lb.

It should be noted that the curves for these figures are for the specific test conditions used by Nicholls. The cooling of the side walls, not done in these tests, would affect

the results. It is not probable that such cooling influences the rate of ignition materially, but it does lower the average rate of burning because of poorer combustion at the sides.

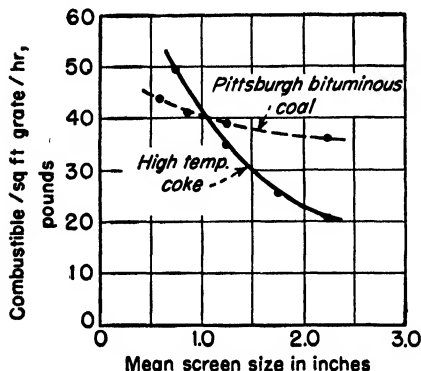


FIG. 11-8. Maximum combustion rate for various sizes of coke and bituminous coal. (P. Nicholls.)

**Secondary Air Requirements.** Figure 11-7 shows the conditions of air supply under all conditions of burning as a special scale in the upper right corner. This is useful in determining the amount of secondary air that must be supplied and mixed with the gases over the fuel bed. Thus it must be remembered that the air shown at the bottom of the charts is primary air only, and not the total air such as might be obtained from calculations of theoretical air requirements.

**Comparison of Various Fuels.** Figure 11-6 shows composite curves for all fuels tested in the  $1\frac{1}{2}$ -by 1-in. size. It is unfortunate that information on other sizes of anthracite, particularly the smaller

sizes, is not available, as this would be pertinent to underfeed burning.

**Maximum Rates of Combustion.** Table 11-7 shows the maximum rate of burning combustible (moisture- and ash-free fuel) for the several fuels tested. As has been explained, no higher rates of combustion than these can be obtained with underfeed

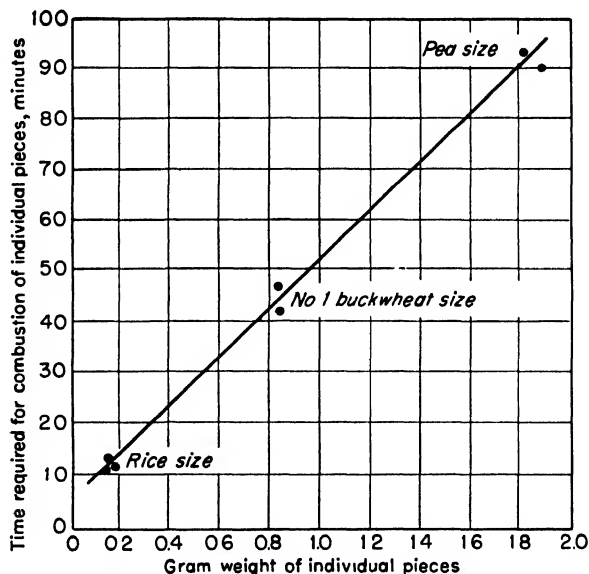


FIG. 11-9. Time required for the combustion of anthracite (plotted against particle size).

burning with any air-supply or fuel-bed manipulation (Table 11-7 was compiled from Fig. 11-6). Figure 11-8 shows the same data for Pittsburgh bituminous coal and high-temperature coke as plotted against fuel size. Parallel information was not obtained for the other fuels, so that it was not possible to plot them against particle size.

### Overfeed Combustion

Nicholls says that with overfeed combustion, such as in a hand-fired furnace, any size of fuel can be burned continuously at any rate by adjusting the air rate and the depth of the fuel bed. However, Johnson<sup>1</sup> found that, for each particle size of anthracite, there is a corresponding very definite time required for its complete combustion. This ranged from 13 min per individual piece of rice coal to 92 min for a single piece of pea size. These figures (see Fig. 11-9) represent optimum conditions of air supply, but the deviation from the mean with various atmospheres and air supplies was slight. For practical purposes, Fig. 11-9 thus shows the maximum rate at which anthracite can be burned under any practical conditions of firing or air supply.

### Summary of Maximum Burning Rates

Based on the above data, actual conditions of maximum burning rates can be summarized as follows:

With **underfeed** firing, the burning zone is always above the incoming coal. Thus, ignition must continuously work downward against the flow of the incoming air. If the cooling effect of this air overcomes the heating effect of the rate of ignition, the

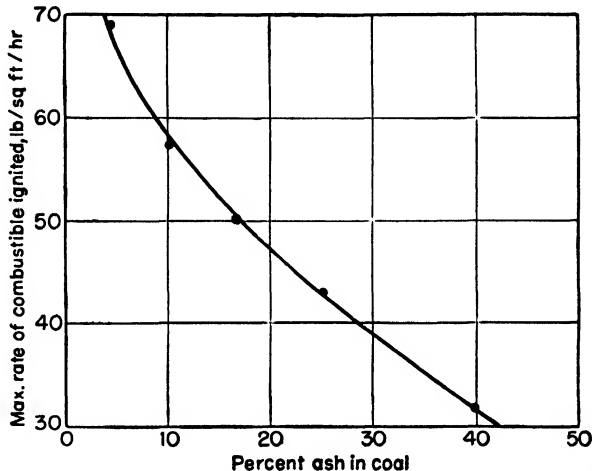


FIG. 11-10. Maximum rates of ignition of anthracite (St. Nicholas rice size, 4-in.-deep fuel bed) with various ash contents (traveling grate). (E. P. Carman and W. T. Reid, *Trans. ASME*, August, 1945.)

fire will necessarily be prevented from spreading to the incoming coal and ultimately will be extinguished. Hence, for each coal, there is a very definite optimum rate of underfeed combustion which cannot be exceeded by increased air supply.

With **overfeed** firing, each piece of coal has a definite time requirement for its complete combustion which is determined by its size and not by the air supply. However, the active fuel-bed zone is constantly creeping toward the incoming fresh coal so that, as the rate of air supply is increased, more pieces are burned simultaneously to give the effect of higher rates of combustion through greater changes in the active fire zone than are possible with underfeeding.

In **cross-firing** anthracite, as on small domestic stokers, it is important to allow each piece of coal to remain in the active fire zone for the time required for its complete combustion.

<sup>1</sup> JOHNSON, ALLEN J., Some Practical Considerations in Connection with Combustion, *Trans. First Anthracite Conference of Lehigh University*, p. 63, 1938.

Table 11-7. Maximum Rate of Combustible Burned at Any Air Rate and Primary Air at This Optimum Rate<sup>1</sup>

(All tests at 80°F primary air temperature)

Fuel	Size, in.	Max combustible, lb/sq ft/hr	Corresponding primary air, lb/sq ft/hr
Pittsburgh bituminous . . . . .	1 × 1½	43	500-550
Westmoreland bituminous . . . . .	1 × 1½	39	500-550
Illinois bituminous . . . . .	1 × 1½	32	400-450
Splint bituminous . . . . .	1 × 1½	51	450-500
Low-temperature coke . . . . .	1 × 1½	+48	+700
High-temperature coke . . . . .	1 × 1½	36	250
Petroleum coke . . . . .	1 × 1½	+77	+650
Anthracite, 8.3 per cent by volume . .	1 × 1½	43	350
Anthracite, 3.5 per cent by volume . .	1 × 1½	27.5	250
Illinois bituminous . . . . .	¾ × 1	41	450
High-temperature coke . . . . .	½ × 1	48	300
High-temperature coke . . . . .	1½ × 2	26	250
High-temperature coke . . . . .	2 × 2½	21	200

<sup>1</sup> From data by P. NICHOLLS, *U.S. Bur. Mines Bull.* 378. Applies to underfed combustion only.

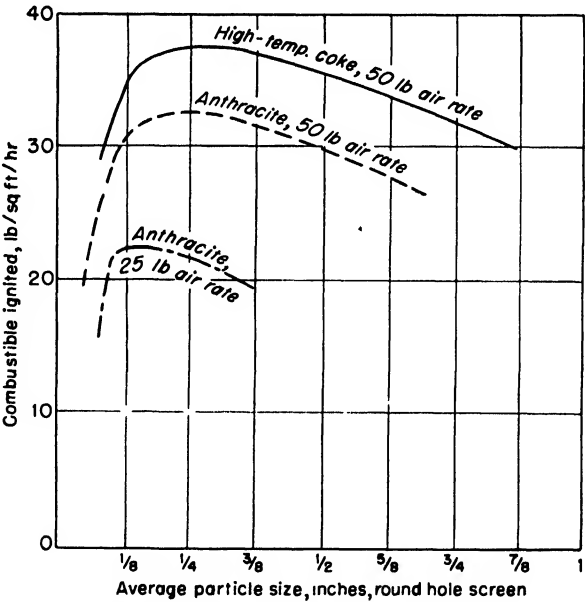


FIG. 11-11. Rate of ignition of coke and anthracite of different particle size. (*E. P. Carman and W. T. Reid, Trans. ASME, August, 1945.*)

**Optimum Burning Rates.** The comparatively small difference in the amount of fixed carbon burned per unit of grate surface with all kinds of coal under equal operating conditions is surprising. According to Cochrane,<sup>1</sup> it is best to burn from 12 to 16 lb of fixed carbon per square foot of hand-fired grate surface and natural draft per hour. On this basis, the approximate rates of combustion for different fuels would be:

<sup>1</sup> "Finding and Stopping Waste in Modern Boiler Rooms," 4th ed., p. 144, Cochrane Corp., Philadelphia, 1928.

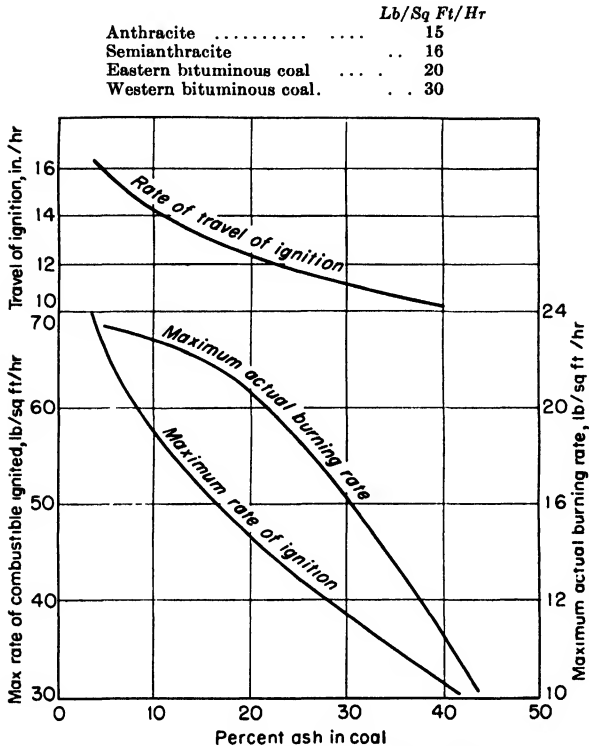


FIG. 11-12. Rate of travel of plane of ignition and rate of ignition in 4-in.-deep beds of St. Nicholas rice anthracite with varying ash content. (E. P. Carman and W. T. Reid, *Trans. ASME*, August, 1945.)

#### Preheated Air for the Combustion of Solid Fuels<sup>1</sup>

Nicholls<sup>1</sup> conducted extensive laboratory tests to determine the effect of preheat upon combustion in both overfeed and underfeed fuel beds. In many instances, the coverage is incomplete in that not so many sizes and kinds of coal were included as might have been desired for handbook reference. However, the work is painstaking, and it is unique in its field. Thus, the following conclusions are presented for the coverage afforded.

**Overfeed Firing.** For overfeed fuel beds (such as hand-firing) it was concluded that preheat increased the rapidity of the actions at the lower part of the bed so that they occurred earlier. The oxygen disappeared at a shorter distance as the preheat increased, there being no oxygen at the  $1\frac{3}{4}$ -in. height with 600 and 800°F air temperatures. The increase of the reactions caused by the preheat decreases with the height above the grate and tends to become constant.

Preheat, therefore, in addition to adding a definite amount of heat, also acts as an accelerator in causing more rapid combustion and in burning a greater weight of fuel per pound of primary air.

Figure 11-13 shows the effect of various degrees of preheat on the CO and CO<sub>2</sub> content of the gases as measured at different distances above the grate. This figure may be used with fair accuracy for the relative rate of burning that will result from maintaining fuel beds of various depths.

<sup>1</sup> *Op. cit.*

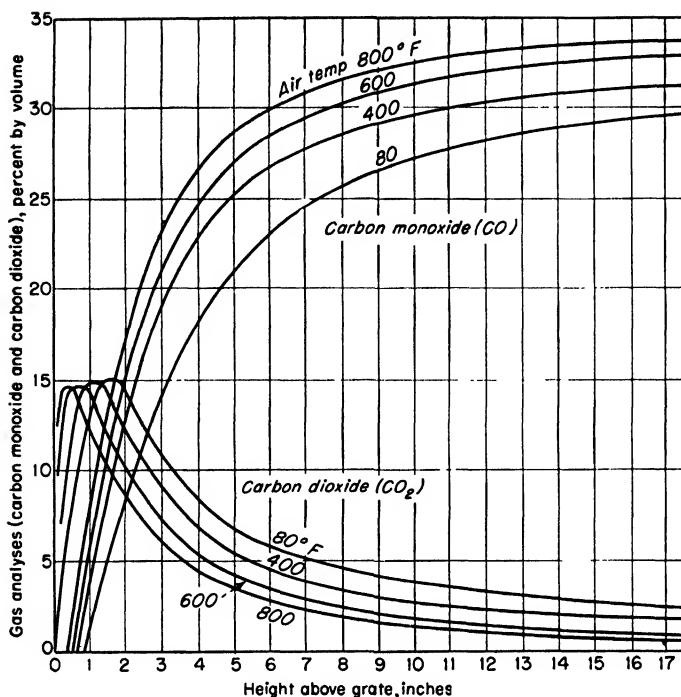


FIG. 11-13. Effect of preheat on gas analyses of overfeed fuel bed of high-temperature coke. (P. Nicholls, U.S. Bureau of Mines, Bull. 378, 1934.)

**Underfeed Burning.** The air temperatures used to study the effect of preheat on underfeed burning were 80 (normal), 200, 300, and 400°F.

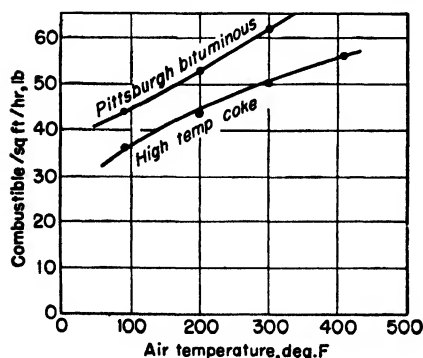


FIG. 11-14. Air temperature vs. rate of ignition—underfeed. (P. Nicholls, U.S. Bureau of Mines, Bull. 378, 1934.)

The rates of ignition increase rapidly with increase of air temperature. Figure 11-14 shows the maximum values of combustible (moisture- and ash-free fuel) burned per square foot per hour plotted against air temperature. Nicholls<sup>1</sup> concluded that at some higher temperature, probably between 1100 and 1200°F, the coke would ignite instantaneously.

Preheat will have little effect on operation at rates of air supply below that at which the ignition curve meets the burning curve (see Fig. 11-5), as it increases the rate of ignition but does not increase the rate of burning, which is the limiting factor. However, above this point, which is the point of fuel-bed equilibrium, preheat permits large increases in the rate of burning with a given rate of air supply but, of course, with the necessity of increasing the secondary air.

<sup>1</sup> *Op. cit.*

Thus, with an air temperature of 80°F, the maximum rate of equilibrium burning was 35.5 lb with 265 lb of air; and, as pointed out in the section on Rate of Combustion vs. Air Supplied, no manipulation of the fuel bed, other than increasing the area of the ignition surface, could increase this rate. With an air temperature of 400°F, the maximum rate of burning would be about 53.5 lb with 390 lb of air.

### THERMAL VALUE OF FUELS

The thermal value<sup>1</sup> of a fuel is the amount of heat generated as a result of its complete combustion. Results are usually expressed in British thermal units (Btu) per pound, calories per gram, or centigrade heat units (Chu).

#### Definitions

A **British thermal unit (Btu)** is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. By this definition, the exact value of a Btu depends upon the initial temperature of the water. As no standard for this factor has been universally accepted, several values for the Btu are in more or less common use, each differing from the other by a *very* slight amount. One of the more common of these is the "**mean Btu**," which is defined as  $\frac{1}{180}$  of the heat required to raise the temperature of one pound of water from 32 to 212°F at a constant atmospheric pressure of 14.696 psia.

Webster's International Dictionary defines the point of measurement as being at or near the point of maximum density of water, 39.1°F.

For most accurate work, the "**International Table**" (IT) Btu, developed during work on the International Steam Tables, is usually used.

**1 mean Btu corresponds to 1.0008 (IT) Btu**

The number of Btu per pound of coal or other solid fuel is commonly expressed as either Btu "**dry**" or Btu "**as-received**," the latter indicating the Btu in the coal in its moist state. Similarly, phrases such as "**as-sampled**" or "**as-fired**" have the same meaning as "**as-received**."

If care has been taken to preserve the sample in an airtight container, between the time the sample was taken and the time that it is analyzed, the "**as-received**" basis more nearly represents the Btu value of the coal as it is used and as purchased.

The "**dry Btu**" is a convenient term for comparison of values among coals of the same kind and size, in order to eliminate the influence of accidental variations in moisture due to shipment or storage conditions.

A **calorie** (also **gram-calorie**) is defined as the quantity of heat required to raise the temperature of one gram of water one degree centigrade. As in the case of the Btu, its exact value depends on the temperature interval chosen. Among those in the most common use are:

The **International Table (IT) calorie**, usually used for the most accurate work, as defined in terms of international electrical units, is equal to  $\frac{1}{860}$  of an international watt-hour or 4.186 international watt-seconds or international joules.

The "**mean calorie**," one-hundredth of the heat required to raise the temperature of one gram of water from 0 to 100°C, is equivalent to 4.187 absolute joules.

**Table 11-8. Conversion of Thermal Units to Energy and Work Equivalents<sup>1</sup>**

Btu	Kcal <sup>a</sup>	Ft-lb	Hp-hr	Kwhr
1	0.252	778.2	0.0003930	0.0002930
3 968	1	3,088.0	0.001560	0.001163
0.001285	0.0003238	1	0.00000050505	0.0000003765
2,544	641.1	$1.98 \times 10^6$	1	0.7455
3,413	860.0	$2.656 \times 10^6$	1.341	1

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 79, McGraw-Hill Book Company, Inc., New York, 1941.

<sup>a</sup> 1 kcal = 1,000 cal.

<sup>1</sup> Also known as calorific or heat value.



The **15° calorie** ( $t = 15^{\circ}\text{C}$ ), expressed  $\text{cal}_{15}$ , is equivalent to 4.185 absolute joules (provisional).

The **20° calorie** ( $t = 20^{\circ}\text{C}$ ), expressed  $\text{cal}_{20}$ , is equivalent to 4.180 absolute joules.

The **centigrade heat unit (Chu)** is the amount of heat required to raise the temperature of one pound of water one degree centigrade.

$$1 \text{ Chu} = 1.8 \text{ Btu} = 453.6 \text{ gram-calories}$$

when mean units are employed in each instance.

**Conversion of gram-calories to Btu.** As a pound is equivalent to 453.59 grams and a degree centigrade is equivalent to  $1.8^{\circ}\text{F}$ , it follows that

$$1 \text{ Btu} = 251.996 \text{ calories}$$

**Table 11-9. Conversion Factors for Energy, Work, and Heat**

Btu to foot-pounds.....	778 2	Foot-pounds to Btu ....	0 001285
Btu to calories .....	252	Calories to Btu .....	0 003968
Btu to horsepower-hours .	0 000393	Horsepower-hours to Btu ..	2,544
Btu to kilowatt-hours .....	0 000293	Kilowatt-hours to Btu ..	3,413

### Higher and Lower Heat Values

The heat value of a fuel as defined is known as the "higher" heat value and is ordinarily accepted as the standard in this country. In the case of fuel containing hydrogen, and this includes practically all fuels in commercial use, there is another value known as the "lower," "net," or "available" heat value, in the determination of which an attempt is made to allow for the latent heat recovered in the condensation of the water vapor formed in the combustion of hydrogen. For example, in the calorimetric determination of the heat value of a fuel containing hydrogen, the products of combustion are cooled to approximately the temperature of the original mixture, say  $62^{\circ}\text{F}$ . In cooling the products to this temperature, the water vapor formed by the combustion of hydrogen is condensed, and the result, expressed in Btu, after being corrected for sulphur and like factors, *i.e.*, the higher heat value, includes the latent heat of water vapor given up in such condensation.

With the weight of water produced per pound of fuel, represented by  $w$  and  $r$ , as a factor which varies with the percentage of hydrogen in the fuel, the moisture in the air and the temperature to which the products of combustion are cooled in the calorimeter,

$$\text{Lower heat value} = (\text{higher heat value}) - wr$$

Too frequently  $r$  is simply taken as the latent heat of steam at either  $32$  or  $212^{\circ}\text{F}$  though in calorimetric work neither of these temperatures is apt to occur.

With the lower heat value so defined, the difference between the higher and the lower or net value will obviously be the total heat of the steam or water vapor as it escapes less the sensible heat of an equivalent weight of water at the temperature of the fuel and of the oxygen before combustion takes place.

The lower heat value is in common use in Great Britain and in most foreign countries. In this country, the higher value is almost universally accepted, and this is the standard recommended by the ASME.

Any attempt to make use of the lower heat value introduces a source of possible error in the proper temperature for use in computation, and advocates of the use of this value are not in entire agreement as to the proper methods of such computations.

To sum up, a theoretically perfect absorption of heat after combustion would condense all the moisture formed in the burning of hydrogen; and, since the efficiency of any apparatus is based upon the performance of a theoretically perfect machine, it appears only logical to charge against the apparatus what would be secured from the theoretically perfect. Further, in the report of the performance of any apparatus, a heat balance offers a method of determining and expressing any loss due to the burn-

ing of hydrogen, and no such test or performance report can be accepted as reliable unless accompanied by a heat balance or by data from which a heat balance may be computed.

**Table 11-10. Typical Heat Values of Various Fuels**

(For use only in general comparisons where more specific heat values are not available)

	Btu/lb	Btu/gal	Btu/cu ft
<b>Solid Fuels<sup>a</sup></b>			
Anthracite . . . .	13,000		
Semianthracite	13,300		
Bituminous coal:			
High-volatile A	14,500		
High-volatile B	13,500		
High-volatile C	12,000		
Medium-volatile	14,200		
Low-volatile	14,500		
Subbituminous A	12,000		
Subbituminous B	10,500		
Subbituminous C	9,000		
Lignite . . . .	7,000		
Peat, air-dried	7,500		
Peat, as-received	2,000		
By-product coke	12,900		
Wood . . . .	9,000 <sup>b</sup>		
Wood, pitch pine	11,000		
<b>Liquid Fuels</b>			
No. 1 (gravity 35-40)		137,300	
No. 2 (gravity 26-35)		141,500	
No. 3 . . . . .			
No. 4 (gravity 24-26)		145,000	
No. 5 (gravity 18-22)		146,500	
No. 6 (gravity 14-16)		148,000	
<b>Gaseous Fuels</b>			
Manufactured gas		. . .	525
Natural gas		. . .	1,000
Propane	21,600	91,500	2,520
Butane	21,200	102,600	3,260
Isobutane . . .	21,300	90,000	3,270
Producer gas:			
Anthracite (Galusha)			140
Bituminous			150
Blast-furnace gas			102

<sup>a</sup> As-received basis unless otherwise noted.

<sup>b</sup> 21,000,000 per cord.

<sup>c</sup> Not included as a designation in code CS12-48.

### Computation of Heat of Combustion from Dulong's Formula

The only accurate and reliable heating value of a fuel is that determined experimentally with a calorimeter, and such determination should correctly be reported as a part of the ultimate or proximate chemical analysis of the fuel.

Approximate heat values may be determined for certain fuels by computation from the ultimate chemical analysis of the fuel. The formula for such computation in most general use and which for most coals gives reasonably accurate results is that of Dulong. This formula, using approximate figures, is

$$\text{Btu/lb} = 14,600C + 62,000 \left( H - \frac{O}{8} \right) + 4,050S$$

the symbols representing the proportionate parts by weight of carbon, hydrogen, oxygen, and sulphur in the fuel, while the coefficients represent the approximate heating values of the constituents with which they appear in the formula. The term

$[H - (O/8)]$  is assumed to contain a correction for the hydrogen in the fuel which is combined with oxygen and exists as moisture.

Dulong's formula will give, as stated, very close approximations for the heat value of most coals, probably within 2 or 3 per cent. There are, however, certain sources of possible error in the use of the formula even for the fuels with which it gives the most accurate results, and since these sources of error offer the explanation of why the formula is not applicable to all fuels, and particularly to gaseous fuels, their discussion seems warranted.

1. Carbon and sulphur are the only elements in coal in a free state, but a portion of these constituents may occur in elementary form. The carbon may be present as graphite or as amorphous carbon, the heating values of which are entirely different. The sulphur may exist as  $FeS_2$  (pyrites). Further, the sulphur may be burned to  $SO_2$  or  $SO_3$ , in the production of which the amount of heat evolved is widely different.

2. If portions of the carbon and hydrogen are combined as hydrocarbons, the heating value of such combinations is far different from what it would be if the elements existed separately, since in such case the heat of combination or of dissociation would have to be considered. This factor makes questionable the heat value of a portion of the carbon and probably of all the hydrogen.

3. The term  $[H - (O/8)]$ , which is assumed to be correct for that portion of hydrogen contained in the moisture, is not a proper assumption, since a portion of the oxygen unquestionably exists in a free state in all fuels.

4. An additional portion of the oxygen is in all probability combined with nitrogen in certain organic nitrates and some may possibly exist in combination as carbonates in mineral matter foreign to the coal.

All these factors tend toward error. While with most coals the error is small, it is unfortunately, with the generally accepted coefficients, one of excess. In the case of gaseous fuels, however, in view particularly of items 2 and 3 above, the chance of error is great. The magnitude of error will depend in such cases upon the individual set of hydrocarbons present in the fuel.

Numerous other formulas of an empirical nature for the determination of the heat value of fuels have been offered by various authorities. Most of these are based upon a series of chemical analyses; and, though they give reasonably accurate results in the case of individual classes of coal, they fail when an attempt is made to apply them not only to other classes of fuel, but even to other classes of coal.

In the case of the usual gases, where the proportionate parts by weight may be readily determined, the heating value may be accurately computed from a table of the heat values of individual constituents, which values have been definitely fixed by numerous calorimetric experiments.

### EFFECT OF HYDROGEN CONTENT ON THE NET OR USEFUL HEAT OF FUELS<sup>1</sup>

During the process of combustion, the hydrogen content of fuels combines with oxygen to form water vapor. As the latent heat of vaporization required for this combination is never utilized under commercial conditions, there is a resultant lowering of the total or higher heat value to a lesser or net amount that represents the heat in the fuel that is actually available for utilization. Despite the fact that this reduction of heat value is appreciable, particularly with fuels high in hydrogen, it is commonly neglected in preparing heat balances and comparisons. A principal reason for failure to deduct the hydrogen loss in making such computations is that the proximate

<sup>1</sup> FIELDNER, A. C., and W. A. SELVIG, Use of Hydrogen-Volatile Matter Ratio in Obtaining the Net Heating Value of American Coals, *U.S. Bur. Mines Tech. Paper* 197, 1918.

Table 11-11. Examples of the Heat Lost Due to Water Vapor from Hydrogen

Kind of fuel	Hydrogen, per cent	Total heat of combustion, Btu	Net heat of combustion, Btu	Heat loss in water vapor at 68°F per cent
Bituminous coal . . . . .	5 18	13,560	13,075	3 6
Anthracite . . . . .	2 50	12,780	12,545	1 8
Fuel oil . . . . .	12 75	18,540	17,345	6.4
Coke . . . . .	0 30	12,500	12,470	0.2

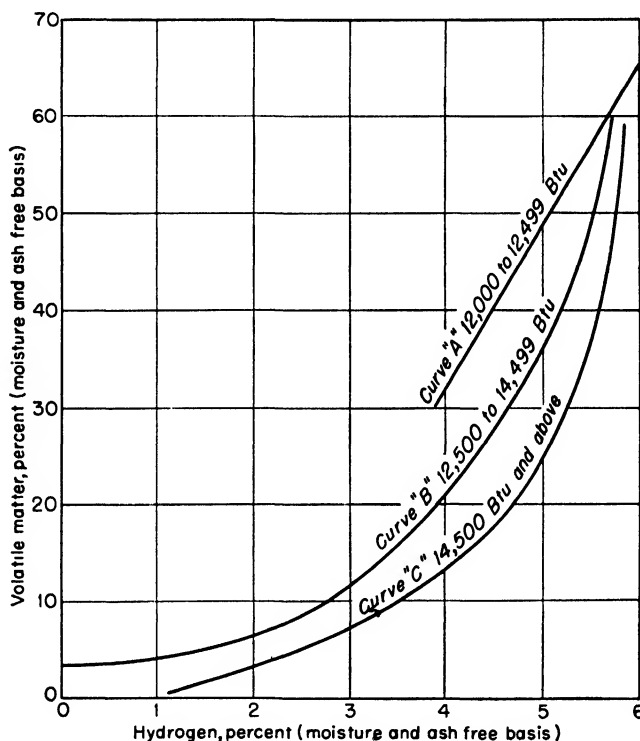


FIG. 11-15. Hydrogen-volatile ratio for American coals. (Fieldner-Selvig.)

*Notes:* All values shown are on an ash- and moisture-free basis. Use Curve "A" for coals of 12,000 to 12,499 Btu (moisture- and ash-free). Use Curve "B" for coals of 12,500 to 14,499 Btu (moisture- and ash-free). Use Curve "C" for coals of 14,500 and higher Btu (moisture- and ash-free). Use 4.3 per cent volatile for coals and lignite below 12,000 Btu.

analysis, commonly used for such determinations, does not give any direct indication of hydrogen content that could be used as a basis for calculation.

Obviously, when the hydrogen content is known, its content by per cent of total fuel can be, and should be, used to correct the total heat to a practical or net value in accord with the following formula:

$$\text{Net heat of combustion} = \text{total heat of combustion} - \frac{H \times 9 \times 1,040}{100}$$

where **total heat of combustion** is the direct result as obtained in a bomb calorimeter

with the water vapor condensed to room temperature, **net heat of combustion** includes a correction for the water in the products of combustion passing off as a vapor at 68°F, and **hydrogen** is expressed in terms of per cent of fuel.

**Correcting for Hydrogen from Proximate Analysis.** Recognizing the need for even approximate correction for hydrogen content from the proximate analysis alone, Fieldner and Selvig plotted curves to show the relation between hydrogen and volatile matter in coal. While admittedly rough, as 1 per cent hydrogen corresponds to a correction of only 94 Btu, these curves are sufficiently accurate for most practical purposes and are far superior to the common practice of neglecting the hydrogen correction altogether.

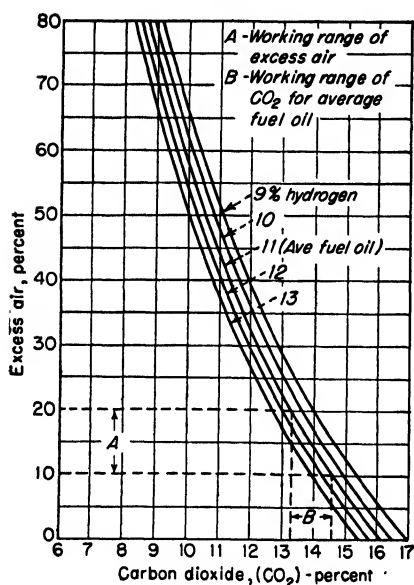


FIG. 11-16. Relation between carbon dioxide ( $\text{CO}_2$ ) and excess air for oils of various hydrogen content. A = working range of excess air. B = working range of  $\text{CO}_2$  for average fuel oil. (*Instruction Book, Oil Burning Equipment, Todd Combustion Equipment, Inc.*)

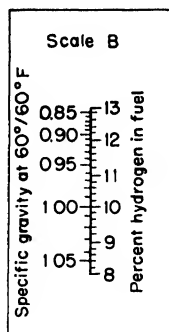
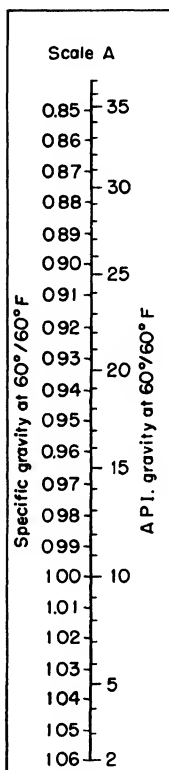


FIG. 11-17. Charts for converting API gravity to specific gravity to hydrogen content. (*Instruction Book, Oil Burning Equipment, Todd Combustion Equipment, Inc.*)

Aided by these curves, shown as Fig. 11-15, the approximate percentage of hydrogen in any coal or lignite may be estimated from the proximate analysis and calorific determination in the following manner:

1. Compute the moisture- and ash-free Btu and volatile matter by the following formulas:

$$\text{Moisture- and ash-free Btu} = \text{Btu} \times \frac{100}{100 - (\text{per cent H}_2\text{O} + \text{per cent ash})}$$

$$\text{Moisture- and ash-free volatile} = \text{per cent volatile} \times \frac{100}{100 - (\text{per cent H}_2\text{O} + \text{per cent ash})}$$

2. Refer to the appropriate curve in Fig. 11-15 for the Btu obtained, and read the percentage of hydrogen corresponding to the given moisture- and ash-free volatile matter.

3. Compute the moisture- and ash-free hydrogen so obtained to the condition in which the remainder of the analysis is stated by the following formula:

$$(\text{Per cent moisture- and ash-free hydrogen}) \times \frac{100 - (\text{per cent H}_2\text{O} + \text{per cent ash})}{100} \\ = \text{per cent hydrogen in coal as received}$$

**Probable Error.** By the use of these curves, which were constructed from 2,000 analyses, the hydrogen content of bituminous coal, subbituminous coal, and anthracite may be estimated from the volatile matter to within 0.6 per cent; for subbituminous coal and lignite 0.8 per cent; and if the coals are weathered the error may approach 1 per cent. The corresponding errors in reducing total to net heat value are: bituminous and anthracite 56 Btu; subbituminous and lignite 75 Btu; and weathered coal 94 Btu.

### Determination of Hydrogen in Oils

**Carbon Dioxide-Excess Air Relationship.** The carbon dioxide-excess air curve varies for oils of different hydrogen content as is shown in Fig. 11-16.<sup>1</sup>

**Hydrogen Content vs. Gravity.** In the event that the hydrogen content of an oil is not known, its approximate value may be obtained from scale *A* and then *B* of Fig. 11-17. The gravity in degrees API is converted to specific gravity (unless the latter is available direct), such as by Fig. 11-17*A*. Figure 11-17*B* is then used to ascertain the corresponding hydrogen content. This figure is also useful in determining the hydrogen-loss component of heat balances, as described in Chap. 12.

## FLAME

The appearance of combustion, *i.e.*, the "look" of the mass of fuel and of the products of combustion, offers to the experienced eye a measure of the temperatures developed. Such methods of necessity offer only the roughest approximations but, in connection with the flame length, are of some value where apparatus for more accurate determination of the extent and degree of combustion is not available.

The physical evidence by which the temperature and the degree and the extent of combustion in a boiler furnace may be judged is the appearance of the flame, the fuel itself being visible but rarely. Flame may be defined as a mass of intensely heated gas in a state of combustion, though it is possible for flame to exist as gas not actually in such state. The luminosity of flame, or the characteristic which gives its visibility, is due to the heating to incandescence of the

unconsumed particles of combustible matter present in the gases, and the variation in the colors of flame is due to the difference in the degree of heat communicated to these particles. The higher the temperature of these particles the whiter the flame. The length and volume of the flame will vary with the combustible elements present and the thoroughness with which the air and combustible elements are mingled; and the shorter the flame, in the absence of any outside cooling medium, the more rapid and complete the combustion.

**Table 11-12. Temperature and Appearance of Flame**

<i>Appearance of Flame</i>	<i>Approx Temp, Deg F</i>
Dark red.....	975
Dull red.....	1290
Dull cherry red ..	1470
Full cherry red..	1650
Clear cherry red...	1830
Deep orange.....	2010
White .....	2370
Bright white ..	2550
Dazzling white ..	2730

<sup>1</sup> "Oil Burning Equipment," p. 15, Todd Combustion Equipment, Inc., New York.

If it were possible for the combustion of any fuel to be complete and instantaneous there would be no visible flame, since both carbon dioxide and water vapor are invisible. Visible flame, then, is evidence of incomplete or noncombustion, but such evidence in the boiler furnace means simply that the combustion has not taken place with sufficient rapidity to evolve heat instantaneously.

It follows from the above that, for a given amount of fuel burned, a short flame will ordinarily mean rapid and complete combustion, a longer flame delayed combustion, and a very long flame imperfect or noncombustion.

**Table 11-13. Air-Gas Flame Temperatures for Various Manufactured and Natural Gases**

Gas	Net Btu/ cu ft	Flame temp, deg F, no excess air
Natural gas.....	904	3565
Natural gas...	1,021	3562
Carbureted water gas.....	493	3700
Coke-oven plus carbureted water gas. . . . .	495	3630
Coal gas (horizontal retorts).....	486	3600
Oil gas.....	496	3630
Producer gas (coke).....	128	3010
Commercial butane . . . . .	2,977	3640
Commercial propane . . . . .	2,371	3660

**Table 11-14. Maximum Flame Temperature of Hydrocarbon Gases Mixed with Air<sup>1</sup>**

Gas	Temp, deg F	Flame speed in 1-in. tube, fps
Methane .. . . .	3416	2 2
Ethane. . . . .	3442	2 8
Propane .. . . .	3497	2 7
Butane . . . . .	3447	2 7
Isobutane . . . . .	3442	2 7
Ethylene . . . . .	3585	5 4
Propylene . . . . .	3510	3 3
Butylene . . . . .	3501	3.2

<sup>1</sup> "Gaseous Fuels," p. 77, AGA, 1948.

### EXPLOSIVE LIMITS OF VARIOUS GASES AND VAPORS<sup>1</sup>

The risk of explosions is frequently present when gases or volatile materials are used in industrial processes. If the temperature of an inflammable volatile liquid is increased gradually, the air above the liquid becomes progressively richer in inflammable vapor. At a certain concentration, the air-vapor mixture can just be ignited with a flame or a spark of sufficient thermal intensity and propagate a flame. This concentration in air in per cent by volume is called the "lower explosive limit," or LEL. As the concentration increases, it becomes easier to ignite the mixture, and the combustion becomes progressively more violent until a maximum is reached. A further increase in concentration will result in a gradual decrease in the violence of explosion until a point is reached where the mixture will no longer propagate a flame but will burn at the point of ignition. This point is called the "upper explosive limit," or UEL.

<sup>1</sup> AMSTUS, JOHN O., Solvent Vapor Control, *Mech. Eng.*, February, 1949, p. 143.

Table 11-15. Mean Ignition Temperatures of Various Gases, Liquids, and Solids<sup>1</sup>

	Temp of ignition, deg F	Flash point, deg F		Temp of ignition, deg F	Flash point, deg F
<b>Gases:</b>			<b>Liquids:</b>		
Acetylene, C <sub>2</sub> H <sub>2</sub> .....	581		Gasoline, regular.....	536	-47
Ammonia, NH <sub>3</sub> .....	1204		Gasoline, 73-octane.....	570	
Carbon monoxide, CO.....	1202-1211		Gasoline, 92-octane.....	734	
Carbon monoxide, CO <sup>a</sup> .....	1292		Gasoline, 100-octane.....	804	
Butane, C <sub>4</sub> H <sub>10</sub> .....	826		Kerosene.....	491	100
Isobutane, C <sub>4</sub> H <sub>10</sub> .....	1010		Methyl alcohol, CH <sub>3</sub> O.....	878	52
Ethane, C <sub>2</sub> H <sub>6</sub> .....	882-1000		Naphtha.....	450-531	-20
Ethylene, C <sub>2</sub> H <sub>4</sub> .....	1022		Gas oil.....	640	150
Hydrogen, H <sub>2</sub> .....	1065		Lubricating oil.....	711	535
Hydrogen sulphide, H <sub>2</sub> S.....	558-687		Pentane, C <sub>5</sub> H <sub>12</sub> .....	527	-40
Methane (marsh gas), CH <sub>4</sub> .....	1200		Turpentine.....	464	95
Propane, C <sub>3</sub> H <sub>8</sub> .....	898-986		<b>Solids:</b>		
Butylene, C <sub>4</sub> H <sub>8</sub> .....	829		Anthracite.....	925	
Hydrocyanic acid, HCN.....	1000		Anthracite, dust.....	570	
Coal gas.....	1105-1612		Bituminous coal.....	766	
<b>Liquids:</b>			Bituminous coal, slack.....	500	
Ethyl alcohol, C <sub>2</sub> H <sub>5</sub> O.....	738-964	54	Cannel coal.....	668	
Ethylene glycol, C <sub>2</sub> H <sub>6</sub> O <sub>2</sub> .....	775	232	Subbituminous coal.....	870	
Ethyl ether, C <sub>4</sub> H <sub>10</sub> O.....	379	-49	Lignite, slack.....	435	
Benzene, C <sub>6</sub> H <sub>6</sub> .....	1078	12	Charcoal, prepared at 500°F.....	650	

<sup>1</sup> Various sources. Subject to considerable variation according to investigator and conditions of test. A guide only.

<sup>a</sup> Mixed with considerable CO<sub>2</sub>.

Table 11-16. Explosion Limits of Various Gases and Vapors

Substance	Max allowable concentration, ppm <sup>a</sup>	Lower explosion limit <sup>b</sup>	Upper explosion limit <sup>b</sup>
Acetic acid.....	10	4.0	
Acetone.....	500	2.15	13.0
Amyl acetate.....	200	1.1	
Benzine (benzol).....	50	1.4	8.0
Butadiene.....	1,000	2.0	11.5
Butanol (butyl alcohol).....	50	1.6	8.5
Butyl acetate.....	200	1.7	15.0
Carbon disulphide.....	20	1.0	50.
Carbon monoxide.....	100	12.5	74.2
Carbon tetrachloride.....	50		
Ethyl acetate.....	400	2.18	11.5
Ethyl alcohol.....	1,000	3.28	19.0
Gasoline.....	500	1.3	6.0
Hydrogen sulphide.....	20	4.3	45.5
Methyl acetate.....	200	4.1	13.9
Methyl alcohol (methanol).....	.....	6.0	36.5
Naphtha.....	500	1.2	6.0
Ozone.....	1		
Pentane.....	1,000	1.4	8.0
Toluene.....	200	1.27	7.0
Turpentine.....	100	0.8	

<sup>a</sup> ppm = parts per million by volume, as adopted by the American Conference of Governmental Industrial Hygienists, in 1947.

<sup>b</sup> Upper and lower explosion limits are expressed in per cent by volume in air.



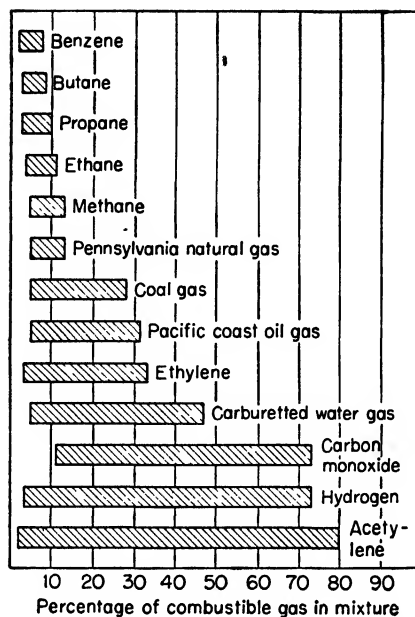


FIG. 11-18. Flammability limits of gases. ("Handbook of Butane-Propane Gases," 1945.)

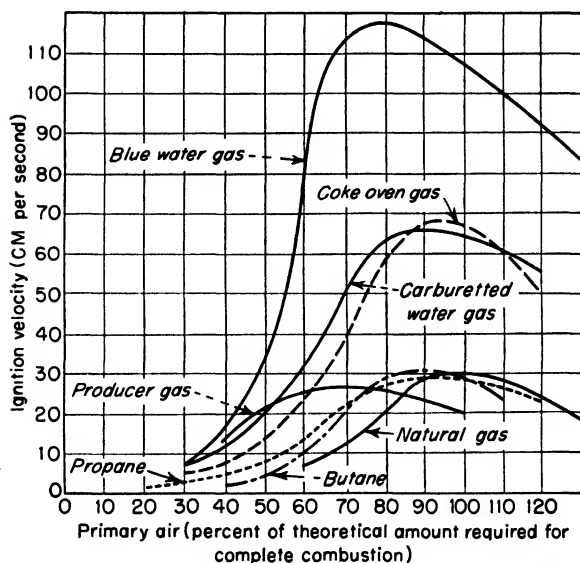


FIG. 11-19. Typical ignition velocity curves for various gases. (AGA Testing Laboratory.)

To prevent explosions, it is necessary to keep the air-vapor mixture below the LEL at all points. A widely accepted practice is to keep the mixture so well blended with air that the calculated concentration never reaches more than 40 per cent of the LEL.

The machine operator or occupants of a vapor-filled room are exposed to health hazards unless vapors are kept below a maximum allowable concentration, such as those shown in Table 11-16. It is important to consider not only the concentration but also the time of exposure; thus the "toxicity ventilation rate" assumes an 8-hr exposure. Many solvents are irritating and narcotic, thus requiring ventilation.

### FUEL-BED DEPTHS<sup>1</sup>

For underfeed firing, at all points above that at which the rate of burning equals the rate of ignition, the fuel bed is said to be in equilibrium in that, for any given rate of primary-air supply, a definite and constant active fire-zone thickness will be maintained.

The exact thickness of this active fire depends upon (1) type of fuel, (2) size of fuel, (3) pounds of primary air per square foot, and (4) temperature of primary air. Items

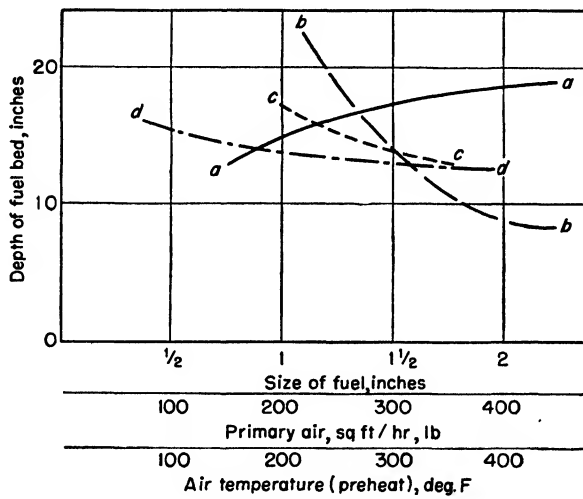


FIG. 11-20. Effect of various factors on equilibrium fuel-bed depths (underfeed firing).

Curve *aa*: Size of fuel vs. fuel-bed depth. High-temperature coke at maximum burning rate (optimum air supply). Curve *bb*: Primary air supplied vs. fuel-bed depth. 1- by 1½-in. high-temperature coke. Curve *cc*: Primary air supplied vs. fuel-bed depth. 1- by 1½-in. anthracite, 3.5 per cent volatile. Curve *dd*: Preheated air vs. fuel-bed depth. High-temperature coke at maximum burning rate (1- by 1½-in. size.)

1 and 2 are matters of major change rather than fuel-bed manipulation. Item 3, amount of primary air, can be moved from very narrow limits only at the expense of a material reduction in the rate of combustion, as has been shown in the section on Rate of Combustion vs. Air Supplied. Changes in item 4, preheat, involve plant design. Thus, by elimination, it can be said that the depth of the active fire zone in underfeed firing is normally beyond the scope of local control.

Figure 11-20 shows the general effect of fuel size, air supply, and preheat on actual equilibrium fuel-bed thicknesses observed by Nicholls.

<sup>1</sup> NICHOLLS, P., *loc. cit.*

**Effect of Wetting Coal on Resistance of Fuel Beds.<sup>1</sup>** It has been established that the wetting of slacks decreases their resistance to the flow of air. This effect is attributed to adhesion of some of the small pieces to the wet surfaces of larger pieces, with the result that fewer small pieces are available to fill the voids between the larger pieces. The net effect is thus one equivalent to removal of part of the fines.

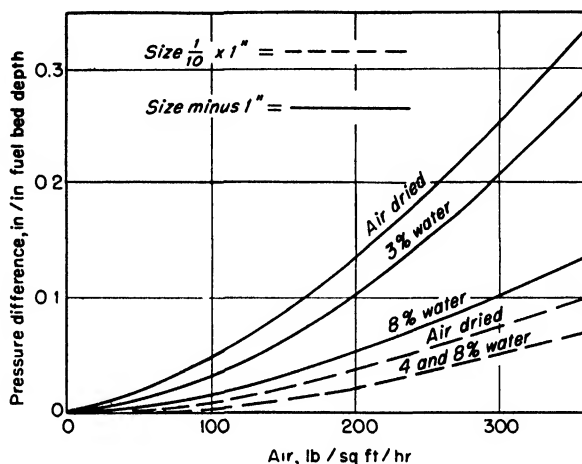


FIG. 11-21. Effect of wetting coal on fuel-bed resistance (Pittsburgh bituminous coal). (U.S. Bureau of Mines, Bull. 404.)

As a practical result, immediately after firing the air will have a more uniform distribution over the area of the bed. This better distribution may be expected to give a more uniform fuel bed and may reduce the tendency to cake.

Figure 11-21 shows fuel-bed resistances for two sizes of Pittsburgh coal with percentages of water from 0 to 8. The maximum amount of water which can be added effectively is limited to the amount that the particular coal will hold without dripping and varies greatly for different coals.

### CLINKER FORMATION AND CONTROL<sup>2</sup>

(See also Ash-softening Temperatures and Ash Composition)

Webster defines clinker as "stony matter vitrified or fused together, as that formed in a furnace from impurities in the coal." The origin of the name is from the Dutch "klinker," a brick so hard that it makes a sonorous sound upon being struck.

The coal, by virtue of its mineral matter, supplies the raw material from which clinker is formed. The process of formation is, however, dependent upon factors largely independent of the mineral matter in the coal. The process is one of physical and chemical reaction in a complex system of silicates and, like all chemical reactions, is aided and abetted by heat and agitation. Time is also a factor.

As the combustion of coal progresses, the combustible matter burns away, leaving the ash more or less in place, but accompanied by a certain amount of shrinkage. The infusible components remain as flaky or fluffy ash; the fusible components sinter or melt into globules, depending on the temperature-composition relations. This material finally works its way down to the grates, during which process the different

<sup>1</sup> U.S. Bur. Mines Bull. 404, p. 148, 1937.

<sup>2</sup> GAUGER, A. W., in Symposium on Significance of Tests of Coal, *ASTM, Proc.*, vol. 37, Part II, 1937. SCHANTZ, C. G., "The Clinkering of Anthracite Coal Ashes," Fifth Annual Anthracite Conference of Lehigh University, May 8, 1947.

mineral components of the ash have an opportunity to come into a more intimate contact. If any component fuses completely, it will flow depending on its viscosity and may trap other ash components as well as unburned combustible material. Reactions may take place, resulting in more fluid systems, such as eutectics. Agitation in the fuel bed aids in the movement of the individual ash particles, making coalescence of fused masses and reaction more easily accomplished.

The important factors at this stage are temperature and properties of the slag. If the individual globules of the slag are fluid so that they reach the grate surface rapidly, and if the temperature on the grates is low enough so that they solidify rapidly, then a loose aggregate of clinker will be formed, which will generally be handled by the furnace mechanism without difficulty (this also presupposes that the slag has a large temperature coefficient of viscosity). If, on the other hand, the temperatures on the grates are high relative to the solidification temperature of the slag globules, the slag will continue to flow, one globule wetting another, and so on, until a large dense clinker is formed. This will disturb air flow and can be removed only with difficulty.

While the fusibility of ash gives an indication of possible clinker and slag trouble, and while it is the best single indicator known, it is generally agreed that it should be considered as indicative only, subject to such other factors as:

1. Properties of coal, including rank, percentage of ash and moisture, ash-softening temperature, composition of ash, caking and coking properties of coal, and size consist of coal.
2. Types, construction, and operation of fuel-burning equipment, including its physical condition.
3. Firing practice, including rate of burning, cleaning of fires, control and distribution of air, preheat, etc.

**General Methods of Reducing Clinker.** The fusion of coal ash in a fuel bed can be decreased (1) by shifting to a higher level the range of temperature at which fusion of the ash occurs, (2) by lowering the temperature of the fuel bed, or (3) by shortening the time the ash is subjected to temperatures at which it fuses.

In addition to these actions, troubles resulting from clinkering will be less as the burning over the area of the fuel bed is more uniform and the bed free from holes. A reduction in caking of coal will give a more uniform bed.

#### Furnace Atmosphere and Ash Characteristics<sup>1</sup>

Research has showed that there is considerable difference in the fusion characteristics of coal ash depending upon whether the coal is burned in a reducing (deficiency of air) or an oxidizing (excess of air) atmosphere. The ash initial-deformation temperature in an oxidizing atmosphere may be considerably higher than that in a reducing atmosphere, with the difference becoming greater with increased iron content of the ash. Experience and

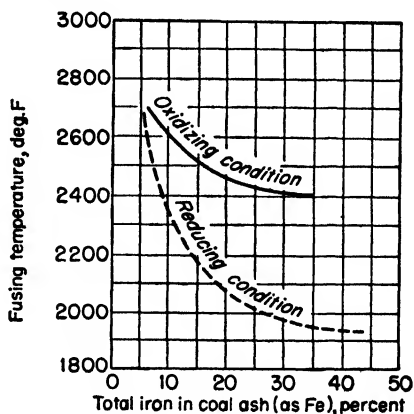


FIG. 11-22. Influence of iron and atmosphere on ash-softening temperature. (Babcock & Wilcox Co.)

<sup>1</sup> ROWAND, W. H., Recent Boiler Design, presented at West Virginia Section ASME, 1947, *Bull.* 3-407, The Babcock & Wilcox Co., New York, 1947.

tests indicate that, when the average true gas temperature leaving the furnace exceeds the oxidizing initial-deformation temperature, cleaning of the ash from the convection surfaces becomes excessive.

Figure 11-22 shows the effect of atmosphere and iron content on the softening point of the ash, showing the temperature difference between the oxidizing and reducing atmospheres for varying content of iron in the ash.

**Clinker Control on Underfeed Stokers.** Unquestionably many factors are of importance in the formation of troublesome clinkers in underfeed stokers. The necessity of having to build up a fire quickly from a banked condition will often cause a black vitreous clinker. The amount of ash is also important. Frequently with a high-ash coal of low ash-softening temperature, no clinker trouble is experienced even at high rates of combustion (50 lb/sq ft/hr), whereas with coal having an ash content of 6.7 per cent it was impossible to reach that rate. The reason for this may be the insulating effect of the large volume of ash formed in burning the high-ash coal. This is, of course, not always true but illustrates that clinker is the result of a complex combination of causes which may either complement or cancel each other.

J. F. Barkley suggests that it might be found that satisfactory conditions from a clinkering standpoint could be had with coals of a lower ash-softening temperature if:

1. Segregation of sizes could be prevented
2. A different size of coal were used
3. Coal of a different mine or seam were used
4. Coal with a lower ash content were used
5. Various adjustments in the stoker were made
6. Better stoker operators were provided
7. Lower CO<sub>2</sub> were carried
8. More boilers were put on the line
9. Certain minor or major changes were made in the equipment

Gauger states that, by certain modifications in design providing for cooling along the side walls, at the tuyères, and on the extension grates, a lowering of the temperature of the caking coal amounting to as much as 1000°F is accomplished. The effect of this on clinkering would be obvious.

A. W. Thorson reminds us that preheated air raises the fuel-bed temperature, thus moving the band of probable clinker up in proportion to the amount of preheat. He also calls attention to the important fact that small zones or areas in the fuel bed at high rates of combustion or high temperatures will cause clinker even though the average of the fuel bed is quite satisfactorily below the clinkering point. Uniformity of fuel bed is thus of considerable importance, as is uniformity of coal feed, of coal distribution, and of air flow. All tend to increase the rate of permissible heat release without clinker for a given coal.

**Pulverized Coal.** See section on Ash-softening Temperatures and Ash Composition.

**Water-gas Generators.** In addition to the considerations cited under Ash-softening Temperatures, clinker troubles are at a minimum on gas generators when the fusion point of the ash is between 2300 and 2500°F. As the ash-fusion temperature is lower or higher than these limits, trouble is apt to develop on the walls or grates of the generator.

**Clinkering with Anthracite.** The Technical Advisory Board of the Anthracite Industry listed the following as being most conducive to the formation of clinker with anthracite:<sup>1</sup>

<sup>1</sup> "Report of the Committee on Clinkering," Technical Advisory Board of the Anthracite Industry, Charles G. Schantz, chairman, Sept. 26, 1941.

1. **Firing methods**, equipment selection, or other factors as determined by the consumer
  - a. Improper firing methods
  - b. Insufficient air (inadequate draft) or unequal air distribution
  - c. Excessively high burning rates (excessive draft)
  - d. Disturbance or agitation of the fuel bed
  - e. Sudden or rapid changes in the fuel bed
  - f. Presence of material foreign to the coal product (or coal as shipped)
  - g. Excessively thin fuel beds
  - h. Air-bound cellars
2. **Equipment design**
  - a. Improper air distribution
  - b. Improper coal distribution (domestic stokers)
  - c. Degradation and segregation of coal (domestic stokers)
3. **Coal preparation**
  - a. Presence of fines (material at least two sizes smaller than the size in question)
  - b. Characteristics of the individual constituents of the coal product, and their effect on each other

In discussing these causes, the Clinker Committee stated that the most common cause for clinker in domestic and small commercial installations was improper firing. They pointed to the necessity for a balance between heat generation and heat distribution through proper air for combustion at all times. Sudden stoppages of air with hot fires, such as even the quick complete closing of dampers by a thermostatically operated damper have been known to cause considerable clinker difficulty. High burning rates, air-bound cellars or boiler rooms, and the burning of foreign material such as garbage were also listed high as causes for clinker.

## TEMPERATURE DATA

Table 11-17. Industrial Temperature Data<sup>1</sup>

<i>Heating Process</i>	<i>Temp, Deg F</i>	<i>Heating Process</i>	<i>Temp, Deg F</i>
Melting refined steel . . . . .	2800	Lead hardening . . . . .	1650
Porcelain burning . . . . .	2600	Annealing steel castings . . . . .	1650
Melting heat-resisting glass . . . . .	2600	Annealing springs . . . . .	1600
Burning firebrick . . . . .	2550	Annealing dies . . . . .	1500
Welding steel tubes . . . . .	2500	Porcelain enameling . . . . .	1500
Copper refining . . . . .	2450	Hardening carbon steel . . . . .	1500
Forging mild steel . . . . .	2400	Annealing malleable castings . . . . .	1450
Melting copper and bronze . . . . .	2300	Annealing rolled steel . . . . .	1450
Melting lead glass . . . . .	2300	Annealing nickel . . . . .	1400
Billet and rivet heating . . . . .	2250	Annealing high-carbon steel . . . . .	1400
Brass melting . . . . .	2200	Annealing band steel . . . . .	1300
High-speed steel hardening . . . . .	2100	Annealing wire . . . . .	1300
Brazing . . . . .	1900	Aluminum melting . . . . .	1200
Vitrification of sewer pipe . . . . .	1850	Glass annealing . . . . .	1200
Blue enameling sheets . . . . .	1800	Tempering high-speed steel . . . . .	1100
Stainless steel . . . . .	1800	Annealing nickel silverware . . . . .	1100
Vitreous enameling . . . . .	1700	Annealing glass lenses . . . . .	1000
Carburizing . . . . .	1650	Reducing iron ore . . . . .	1000

<sup>1</sup> Johns-Manville, "Data Sheet," In-3008.

Table 11-18. Typical Exit-gas Temperatures from Various Furnaces

<i>Furnace</i>	<i>Deg F</i>	<i>Furnace</i>	<i>Deg F</i>
Cement kilns, dry process . . . . .	1200-1500	Gas retorts, nonregenerative . . . . .	1300-1500
Cement kilns, wet process . . . . .	800-1200	Oil stills . . . . .	900-1000
Copper refining . . . . .	1500-2000	Glassmaking . . . . .	800-1000
Beehive coke ovens . . . . .	2000-2300	Nickel refining . . . . .	2500-3000
Heating and puddling furnaces . . . . .	1700-2000	Zinc refining . . . . .	1750-2000
Open-hearth furnaces . . . . .	850-1100		



## Legend to Numbers in Fig. 11-23

1. **Critical Range.** In this range steels undergo internal atomic changes which radically affect the properties of the material.
2. **Lower Critical Temperature ( $A_1$ ).** Termed  $Ac_1$  on heating,  $Ar_1$  on cooling. Below  $Ac_1$  structure ordinarily consists of ferrite and pearlite (see 14 and 17 below). On heating through  $Ac_1$ , the solid ferrite and the solid pearlite begin to dissolve in each other to form austenite (see 15 below), which is nonmagnetic. This dissolving action continues on heating through the critical range until the solid solution is complete at the upper critical temperature.
3. **Upper Critical Temperature ( $A_3$ ).** Termed  $Ac_3$  on heating,  $Ar_3$  on cooling. Above this temperature the structure consists of austenite, which coarsens with increasing time and temperature. Upper critical temperature is lowered as carbon increases to 0.85 per cent (eutectoid point).
4. **Annealing** consists of heating steels to slightly above  $Ac_3$ , holding for austenite to form, then slowly cooling in order to produce small grain size, softness, good ductility, and other properties. On cooling slowly, the austenite transforms to ferrite and pearlite.
5. **Normalizing** is similar to annealing except that cooling is done in still air. On cooling, austenite transforms giving somewhat higher strength and hardness and slightly less ductility than in annealing.
6. **Forging range** extends to several hundred degrees above the upper critical temperature.
7. **Burning range** is above the forging range. Burned steel cannot be cured except by remelting.
8. **Stress relieving** consists of heating to a range definitely below the lower critical temperature, holding for 1 hr or more per inch of thickness, then slowly cooling. Purpose is to allow the steel to relieve itself of locked-up stresses.
9. **Blue brittle range** occurs approximately at 300 to 700°F, in which range steels are more brittle than above or below this range. Peening or working of steel should not be done in this range.
10. **Preheating for welding** is carried out to prevent crack formation. See Tempil Preheating Chart for recommended temperatures for various steels and nonferrous metals.
11. **Carburizing** consists of dissolving carbon into surface of steel by heating to above critical range in presence of carburizing compounds.
12. **Nitriding** consists of heating certain special steels to about 1000°F for long periods in the presence of ammonia gas. Nitrogen is absorbed into the surface to produce extremely hard "skins."
13. **Spheroidizing** consists of heating to just below the critical range to put the cementite constituent of pearlite in globular form. This produces softness and in many cases good machinability.
14. **Ferrite** is practically pure iron (in plain carbon steels) existing below the lower critical temperature. It is magnetic and has very slight solid solubility for carbon.
15. **Austenite** is the nonmagnetic form of iron and has the power to dissolve carbon and alloying elements.
16. **Cementite**, or iron carbide, is a chemical compound of iron and carbon,  $Fe_3C$ .
17. **Pearlite** is a mechanical mixture of ferrite and cementite.
18. **Eutectoid steel** contains approximately 0.85% carbon.
19. **Martensite** is an extremely hard constituent of steels, formed by the rapid transformation of austenite.
20. **Flaking** occurs in many alloy steels and is a defect characterized by localized microcracking and "flakelike" fracturing. It is usually attributed to hydrogen bursts. Cure consists of cycle cooling to at least 600°F before air cooling.
21. **Open or rimming steel** is not completely deoxidized and the ingot solidifies with blowholes.
22. **Killed steel** has been deoxidized at least sufficiently to solidify without appreciable gas evolution.
23. **A Simple Rule:** Brinell hardness divided by 2, times 1,000, equals approximate tensile strength in pounds per square inch. (200 Brinell +  $2 \times 1,000$  = approx 100,000 tensile strength, psi.)



Table 11-19. Temperature Conversion Table

0 to 100											
Deg C		Deg F	Deg C		Deg F	Deg C		Deg F	Deg C		Deg F
-17 8	<b>0</b>	32 0	-3 89	<b>25</b>	77 0	10 0	<b>50</b>	122 0	23 9	<b>75</b>	167.0
-17 2	<b>1</b>	33 8	-3 33	<b>26</b>	78 8	10 6	<b>51</b>	123 8	24 4	<b>76</b>	168 8
-16 7	<b>2</b>	35 6	-2 78	<b>27</b>	80 6	11.1	<b>52</b>	125 6	25 0	<b>77</b>	170 6
-16 1	<b>3</b>	37.4	-2 22	<b>28</b>	82.4	11 7	<b>53</b>	127 4	25 6	<b>78</b>	172.4
-15 6	<b>4</b>	39.2	-1 67	<b>29</b>	84.2	12.2	<b>54</b>	129.2	26.1	<b>79</b>	174 2
-15 0	<b>5</b>	41.0	-1 11	<b>30</b>	86 0	12 8	<b>55</b>	131 0	26 7	<b>80</b>	176 0
-14 4	<b>6</b>	42 8	-0 56	<b>31</b>	87 8	13 3	<b>56</b>	132 8	27 2	<b>81</b>	177.8
-13 9	<b>7</b>	44 6	0	<b>32</b>	89 6	13.9	<b>57</b>	134 6	27 8	<b>82</b>	179.6
-13 3	<b>8</b>	46 4	0 56	<b>33</b>	91 4	14 4	<b>58</b>	136 4	28 3	<b>83</b>	181 4
-12 8	<b>9</b>	48 2	1.11	<b>34</b>	93 2	15 0	<b>59</b>	138 2	28 9	<b>84</b>	183.2
-12 2	<b>10</b>	50 0	1 67	<b>35</b>	95 0	15.6	<b>60</b>	140 0	29 4	<b>85</b>	185 0
-11 7	<b>11</b>	51 8	2 22	<b>36</b>	96 8	16 1	<b>61</b>	141 8	30 0	<b>86</b>	186 8
-11 1	<b>12</b>	53 6	2 78	<b>37</b>	98 6	16 7	<b>62</b>	143 6	30 6	<b>87</b>	188 6
-10 6	<b>13</b>	55 4	3 33	<b>38</b>	100 4	17 2	<b>63</b>	145 4	31 1	<b>88</b>	190 4
-10 0	<b>14</b>	57.2	3.89	<b>39</b>	102 2	17 8	<b>64</b>	147 2	31 7	<b>89</b>	192 2
- 9 44	<b>15</b>	59 0	4 44	<b>40</b>	104 0	18 3	<b>65</b>	149 0	32.2	<b>90</b>	194 0
- 8 89	<b>16</b>	60 8	5 00	<b>41</b>	105 8	18 9	<b>66</b>	150 8	32 8	<b>91</b>	195 8
- 8 33	<b>17</b>	62 6	5 56	<b>42</b>	107 6	19 4	<b>67</b>	152 6	33 3	<b>92</b>	197 6
- 7 78	<b>18</b>	64 4	6 11	<b>43</b>	109 4	20 0	<b>68</b>	154 4	33 9	<b>93</b>	199 4
- 7.22	<b>19</b>	66.2	6.67	<b>44</b>	111 2	20 6	<b>69</b>	156 2	34 4	<b>94</b>	201 2
- 6 67	<b>20</b>	68 0	7 22	<b>45</b>	113 0	21 1	<b>70</b>	158 0	35 0	<b>95</b>	203 0
- 6 11	<b>21</b>	69 8	7 78	<b>46</b>	114 8	21 7	<b>71</b>	159 8	35 6	<b>96</b>	204 8
- 5 56	<b>22</b>	71 6	8 33	<b>47</b>	116 6	22 2	<b>72</b>	161 6	36 1	<b>97</b>	206 6
- 5 00	<b>23</b>	73 4	8 89	<b>48</b>	118 4	22 8	<b>73</b>	163 4	36 7	<b>98</b>	208 4
- 4 44	<b>24</b>	75 2	9 44	<b>49</b>	120 2	23 3	<b>74</b>	165 2	37 2	<b>99</b>	210 2
									37 8	<b>100</b>	212 0

## 100 to 1000

Deg C		Deg F	Deg C		Deg F	Deg C		Deg F	Deg C		Deg F
38	<b>100</b>	212	160	<b>320</b>	608	288	<b>550</b>	1022	410	<b>770</b>	1418
43	<b>110</b>	230	166	<b>330</b>	626	293	<b>560</b>	1040	416	<b>780</b>	1436
49	<b>120</b>	248	171	<b>340</b>	644	299	<b>570</b>	1058	421	<b>790</b>	1454
54	<b>130</b>	266	177	<b>350</b>	662	304	<b>580</b>	1076	427	<b>800</b>	1472
60	<b>140</b>	284	182	<b>360</b>	680	310	<b>590</b>	1094	432	<b>810</b>	1490
66	<b>150</b>	302	188	<b>370</b>	698	316	<b>600</b>	1112	438	<b>820</b>	1508
71	<b>160</b>	320	193	<b>380</b>	716	321	<b>610</b>	1130	443	<b>830</b>	1526
77	<b>170</b>	338	199	<b>390</b>	734	327	<b>620</b>	1148	449	<b>840</b>	1544
82	<b>180</b>	356	204	<b>400</b>	752	332	<b>630</b>	1166	454	<b>850</b>	1562
88	<b>190</b>	374	210	<b>410</b>	770	338	<b>640</b>	1184	460	<b>860</b>	1580
93	<b>200</b>	392	216	<b>420</b>	788	343	<b>650</b>	1202	466	<b>870</b>	1598
99	<b>210</b>	410	221	<b>430</b>	806	349	<b>660</b>	1220	471	<b>880</b>	1616
100	<b>212</b>	413 6	227	<b>440</b>	824	354	<b>670</b>	1238	477	<b>890</b>	1634
104	<b>220</b>	428	232	<b>450</b>	842	360	<b>680</b>	1256	482	<b>900</b>	1652
110	<b>230</b>	446	238	<b>460</b>	860	366	<b>690</b>	1274	488	<b>910</b>	1670
			243	<b>470</b>	878	371	<b>700</b>	1292	493	<b>920</b>	1688
116	<b>240</b>	464									
121	<b>250</b>	482	249	<b>480</b>	896	377	<b>710</b>	1310	499	<b>930</b>	1706
127	<b>260</b>	500	254	<b>490</b>	914	382	<b>720</b>	1328	504	<b>940</b>	1724
132	<b>270</b>	518	260	<b>500</b>	932	388	<b>730</b>	1346	510	<b>950</b>	1742
138	<b>280</b>	536	266	<b>510</b>	950	393	<b>740</b>	1364	516	<b>960</b>	1760
143	<b>290</b>	554	271	<b>520</b>	968	399	<b>750</b>	1382	521	<b>970</b>	1778
149	<b>300</b>	572	277	<b>530</b>	986	404	<b>760</b>	1400	527	<b>980</b>	1796
154	<b>310</b>	590	282	<b>540</b>	1004				532	<b>990</b>	1814
									538	<b>1000</b>	1832

Read known temperature in boldface type. Corresponding temperature in degrees Fahrenheit will be found in column to the right. Corresponding temperature in degrees centigrade will be found in column to the left.

Table 11-19. Temperature Conversion Table. (Continued)

1000 to 2000											
Deg C		Deg F	Deg C		Deg F	Deg C		Deg F	Deg C		Deg F
538	1000	1832	677	1250	2282	816	1500	2732	954	1750	3182
543	1010	1850	682	1260	2300	821	1510	2750	960	1760	3200
549	1020	1868	688	1270	2318	827	1520	2768	966	1770	3218
554	1030	1886	693	1280	2336	832	1530	2786	971	1780	3236
560	1040	1904	699	1290	2354	838	1540	2804	977	1790	3254
566	1050	1922	704	1300	2372	843	1550	2822	982	1800	3272
571	1060	1940	710	1310	2390	849	1560	2840	988	1810	3290
577	1070	1958	716	1320	2408	854	1570	2858	993	1820	3308
582	1080	1976	721	1330	2426	860	1580	2876	999	1830	3326
588	1090	1994	727	1340	2444	866	1590	2894	1004	1840	3344
593	1100	2012	732	1350	2462	871	1600	2912	1010	1850	3362
599	1110	2030	738	1360	2480	877	1610	2930	1016	1860	3380
604	1120	2048	743	1370	2498	882	1620	2948	1021	1870	3398
610	1130	2066	749	1380	2516	888	1630	2966	1027	1880	3416
616	1140	2084	754	1390	2534	893	1640	2984	1032	1890	3434
621	1150	2102	760	1400	2552	899	1650	3002	1038	1900	3452
627	1160	2120	766	1410	2570	904	1660	3020	1043	1910	3470
632	1170	2138	771	1420	2588	910	1670	3038	1049	1920	3488
638	1180	2156	777	1430	2606	916	1680	3056	1054	1930	3506
643	1190	2174	782	1440	2624	921	1690	3074	1060	1940	3524
649	1200	2192	788	1450	2642	927	1700	3092	1066	1950	3542
654	1210	2210	793	1460	2660	932	1710	3110	1071	1960	3560
660	1220	2228	799	1470	2678	938	1720	3128	1077	1970	3578
666	1230	2246	804	1480	2696	943	1730	3146	1082	1980	3596
671	1240	2264	810	1490	2714	949	1740	3164	1088	1990	3614
									1093	2000	3632
2000 to 3000											
Deg C		Deg F	Deg C		Deg F	Deg C		Deg F	Deg C		Deg F
1093	2000	3632	1232	2250	4082	1371	2500	4532	1510	2750	4982
1099	2010	3650	1238	2260	4100	1377	2510	4550	1516	2760	5000
1104	2020	3668	1243	2270	4118	1382	2520	4568	1521	2770	5018
1110	2030	3686	1249	2280	4136	1388	2530	4586	1527	2780	5036
1116	2040	3704	1254	2290	4154	1393	2540	4604	1532	2790	5054
1121	2050	3722	1260	2300	4172	1399	2550	4622	1538	2800	5072
1127	2060	3740	1266	2310	4190	1404	2560	4640	1543	2810	5090
1132	2070	3758	1271	2320	4208	1410	2570	4658	1549	2820	5108
1138	2080	3776	1277	2330	4226	1416	2580	4676	1554	2830	5126
1143	2090	3794	1282	2340	4244	1421	2590	4694	1560	2840	5144
1149	2100	3812	1288	2350	4262	1427	2600	4712	1566	2850	5162
1154	2110	3830	1293	2360	4280	1432	2610	4730	1571	2860	5180
1160	2120	3848	1299	2370	4298	1438	2620	4748	1577	2870	5198
1166	2130	3866	1304	2380	4316	1443	2630	4766	1582	2880	5216
1171	2140	3884	1310	2390	4334	1449	2640	4784	1588	2890	5234
1177	2150	3902	1316	2400	4352	1454	2650	4802	1593	2900	5252
1182	2160	3920	1321	2410	4370	1460	2660	4820	1599	2910	5270
1188	2170	3938	1327	2420	4388	1466	2670	4838	1604	2920	5288
1193	2180	3956	1332	2430	4406	1471	2680	4856	1610	2930	5306
1199	2190	3974	1338	2440	4424	1477	2690	4874	1616	2940	5324
1204	2200	3992	1343	2450	4442	1482	2700	4892	1621	2950	5342
1210	2210	4010	1349	2460	4460	1488	2710	4910	1627	2960	5360
1216	2220	4028	1354	2470	4478	1493	2720	4928	1632	2970	5378
1221	2230	4046	1360	2480	4496	1499	2730	4946	1638	2980	5396
1227	2240	4064	1366	2490	4514	1504	2740	4964	1643	2990	5414
									1649	3000	5432

Conversion formula:

$$\text{Deg C} = \frac{5}{9}(\text{deg F} - 32)$$

$$\text{Deg F} = \frac{9}{5} \text{deg C} + 32$$

Interpolation values for above tables:

Deg C.....	1	2	3	4	5
Deg F.....	1.8	3.6	5.4	7.2	9.0
Deg F.....	1	2	3	4	5
Deg C.....	0.56	1.11	1.67	2.22	2.78

**Table 11-20. Volume and Weight of Air**  
(At atmospheric pressure)

Temp, deg F	Volume, cu ft/lb	Weight, lb/cu ft	Temp, deg F	Volume, cu ft/lb	Weight, lb/cu ft
32	12.390	0.080710	260	18.135	0.055142
50	12.843	0.077863	270	18.387	0.054386
60	13.095	0.076365	280	18.639	0.053651
70	13.347	0.074923	290	18.891	0.052935
80	13.599	0.073535	300	19.143	0.052238
90	13.851	0.072197	320	19.647	0.050898
100	14.103	0.070907	340	20.151	0.049625
110	14.355	0.069662	360	20.655	0.048414
120	14.607	0.068460	380	21.159	0.047261
130	14.859	0.067299	400	21.663	0.046162
140	15.111	0.066177	425	22.293	0.044857
150	15.363	0.065092	450	22.923	0.043624
160	15.615	0.064041	475	23.554	0.042456
170	15.867	0.063024	500	24.184	0.041350
180	16.119	0.062039	525	24.814	0.040300
190	16.371	0.061084	550	25.444	0.039302
200	16.623	0.060158	575	26.074	0.038352
210	16.875	0.059259	600	26.704	0.037448
212	16.925	0.059084	650	27.964	0.035760
220	17.127	0.058388	700	29.224	0.034219
230	17.379	0.057541	750	30.484	0.032804
240	17.631	0.056718	800	31.744	0.031502
250	17.883	0.055919	850	33.004	0.030299

## CHAPTER 12

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### DETERMINATION AND CALCULATION OF HEAT BALANCE

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## HEAT BALANCES

A heat balance shows the distribution of the heating value of the fuel used as balanced against the ultimate disposition of this heat as divided into its several components. Obviously the two sides of such an equation must balance.

For any fuel, such a balance can be expressed as in Table 12-1.

**Table 12-1. Items Comprising a Boiler Heat Balance**

<i>Input</i>	<i>Output</i> [Useful Heat (Boiler Output) plus Losses]
Heat input in the fuel used =	$\left\{ \begin{array}{l} 1. \text{ Heat absorbed by boiler and other apparatus, as output} \\ 2. \text{ Dry flue-gas loss} \\ 3. \text{ Loss due to evaporation of water formed by hydrogen burned} \\ 4. \text{ Loss due to evaporation of moisture in the fuel} \\ 5. \text{ Loss due to moisture in the air} \\ 6. \text{ Loss due to incomplete combustion (CO)} \\ 7. \text{ Loss due to unconsumed carbon in the refuse} \\ 8. \text{ Loss due to radiation and unaccounted for} \end{array} \right.$

In this chapter, three methods of computing such a heat balance are given. All are based on the same fundamentals as shown in Table 12-1, the only difference being the ascending degree of accuracy and the correspondingly ascending degree of detail required for solution. These methods are:

1. Rough field check of heat balance
2. Nomograph method of computing heat balance
3. Chemical-mathematical method of computing heat balance from ultimate analyses (exact method)

### METHOD 1. ROUGH FIELD CHECK OF HEAT BALANCE

It is frequently necessary and convenient to make rough field checks of heat balance where little information is available other than the carbon dioxide percentages and temperatures of the stack gases.

This may be accomplished by means of Tables 12-2 to 12-9, as follows:

#### **Heat Balance from Charts:**

1. Find the dry flue-gas loss from Table 12-2 (anthracite), 12-3 (bituminous coal), 12-4 (oil), 12-5 (natural gas), 12-6 (water gas), or 12-7 (propane).
2. Find the hydrogen loss from Table 12-8 (gaseous fuels), or 12-9 (liquid and solid fuels).
3. Allow for an estimated radiation loss from the boiler. This should range from about 1 to 2 per cent for large well-insulated power boilers to 30 per cent for domestic warm-air furnaces. Hence some experience is needed for accuracy, but as boilers of the same class are usually those being compared, this should not greatly affect the comparison.
4. Allow for unconsumed carbon in the refuse, **in the case of solid fuels only.** This will seldom exceed 4 to 5 per cent and therefore will not greatly affect the approximate heat balance.
5. Subtract the sum of 1 to 4 from 100 per cent. The result will be the approximate heat absorbed or efficiency.

**Hydrogen Loss Important with Liquid and Gaseous Fuels.** It is common practice to neglect hydrogen losses in reporting oil and gas heat balances. This is highly erroneous, since, while in solid fuels the hydrogen loss seldom exceeds 4 per cent and can be safely overlooked, in oil or gas it may reach 15 per cent to become a major item. Thus, in determining approximate heat balances for liquid and gaseous fuels, hydrogen losses, as from Tables 12-8 and 12-9, should always be included.

**Table 12-2. Field Check: Dry Flue-gas Loss, Anthracite**  
(Per cent, based on 13,000 Btu/lb)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room									
	400	450	500	550	600	650	700	750	800	900
3.0	47.6	53.8	60.0	66.2	72.5	78.6	84.7	90.8	96.9	
4.0	36.1	40.3	45.0	50.0	54.7	60.0	64.2	69.5	74.5	83.2
5.0	29.2	33.1	36.9	40.7	44.6	48.2	51.6	55.3	58.5	66.9
5.5	26.5	30.0	33.9	37.7	41.0	43.5	47.3	50.7	53.8	61.0
6.0	24.2	27.6	30.8	33.9	37.3	40.4	43.4	46.4	49.6	55.6
6.5	22.3	25.4	28.4	31.5	34.4	37.5	40.2	43.2	46.1	51.2
7.0	21.1	23.8	26.6	29.2	31.9	34.6	37.6	40.2	42.8	47.9
7.5	20.0	22.3	24.6	27.3	30.0	32.3	35.0	37.7	40.2	45.0
8.0	18.4	20.8	23.3	25.8	28.3	30.5	32.8	35.3	37.7	42.3
8.5	17.7	19.9	21.9	24.2	26.3	28.5	30.6	33.0	35.3	40.0
9.0	16.6	18.6	20.8	22.8	25.0	27.1	29.2	31.4	33.5	37.7
9.5	15.8	17.8	20.0	22.0	23.9	25.9	27.8	29.9	31.8	35.6
10.0	15.0	16.9	18.8	20.7	22.7	24.6	26.5	28.4	30.4	34.2
10.5	14.2	16.1	18.0	19.9	21.7	23.6	25.4	27.1	28.8	32.3
11.0	13.7	15.3	16.9	18.7	20.4	22.2	23.8	25.4	27.2	30.6
11.5	13.1	14.6	16.1	17.7	19.5	21.2	22.9	24.5	26.1	29.2
12.0	12.5	14.0	15.6	17.2	18.8	20.3	21.9	23.6	25.2	28.4
12.5	12.2	13.6	15.1	16.6	18.1	19.6	21.1	22.6	24.1	27.2
13.0	11.6	13.0	14.4	15.8	17.3	18.7	20.1	21.6	23.1	26.2
13.5	11.0	12.5	13.9	15.4	16.9	18.3	19.6	20.9	22.2	25.4
14.0	10.8	12.1	13.4	14.7	16.1	17.6	18.8	20.1	21.5	24.6

**Table 12-3. Field Check: Dry Flue-gas Loss, Bituminous Coal**  
(Per cent, based on 14,000 Btu/lb)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room									
	400	450	500	550	600	650	700	750	800	900
3.0	46.0	51.8	57.7	63.4	69.1	74.7	80.5	86.2	92.0	97.7
4.0	33.8	38.1	42.3	46.5	50.7	54.9	59.2	63.5	67.7	71.9
5.0	27.5	31.0	34.4	37.9	41.4	44.7	48.2	51.6	55.1	58.5
5.5	24.9	28.0	31.1	34.2	37.4	40.4	43.5	46.6	49.7	52.8
6.0	22.8	25.7	28.6	31.4	34.3	37.1	39.9	42.8	45.6	48.4
6.5	21.1	23.8	26.4	29.0	31.6	34.2	36.9	39.6	42.2	44.8
7.0	19.6	22.1	24.6	27.0	29.5	31.9	34.4	36.8	39.3	41.7
7.5	18.5	20.7	23.1	25.4	27.7	30.0	32.4	34.6	36.9	39.0
8.0	17.5	19.7	21.7	24.0	26.2	28.3	30.5	33.7	34.9	37.1
8.5	16.5	18.5	20.6	22.6	24.7	26.7	28.8	30.9	32.9	34.9
9.0	15.5	17.5	19.5	21.4	23.4	25.3	27.2	29.2	31.2	33.1
9.5	14.7	16.6	18.4	20.3	22.2	23.9	25.8	27.6	29.5	31.3
10.0	14.0	15.8	17.6	19.3	21.0	22.7	24.5	26.3	28.1	29.8
10.5	13.4	15.1	16.8	18.4	20.1	21.7	23.4	25.1	26.8	28.4
11.0	12.9	14.5	16.1	17.7	19.3	20.9	22.6	24.2	25.8	27.4
11.5	12.3	13.8	15.4	17.0	18.5	20.0	21.5	23.2	24.7	26.2
12.0	11.8	13.3	14.8	16.3	17.8	19.2	20.7	22.2	23.7	25.2
12.5	11.5	13.0	14.4	15.8	17.3	18.8	20.2	21.6	23.0	24.4
13.0	11.0	12.4	13.8	15.1	16.5	17.8	19.2	20.6	22.0	23.3
13.5	10.5	11.8	13.2	14.5	15.8	17.1	18.5	19.8	21.1	22.4
14.0	10.2	11.5	12.8	14.1	15.4	16.6	17.9	19.2	20.5	21.8

**Table 12-4. Field Check: Dry Flue-gas Loss, Oil**

(Per cent, based on 19,250 Btu/lb)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room										
	400	450	500	550	600	650	700	750	800	850	900
3 0	38 8	43.6	48 5	53 3	58.1	63.0	67.8	72 6	77.5	82.4	87.2
4.0	27 9	31 4	34.9	38.3	41.8	45.3	48 8	52 3	55.8	59 3	62 8
5.0	22 7	25.5	28 3	31.1	34.0	36 9	39 7	42.5	45 3	48 2	51 1
5.5	20 7	23.2	25 8	28.4	31.0	33 6	36 2	38.7	41.3	43 9	46 5
6.0	18.9	21.3	23 7	26.1	28.4	30.8	33.2	35.5	37.8	40 3	42.6
6 5	17.5	19.7	21 9	24 1	26 2	28 4	30 6	32 8	35 0	37 2	39 4
7.0	16.4	18.5	20.6	22 6	24.6	26.7	28.8	30 8	32 9	35 0	37.0
7.5	15 4	17.4	19 3	21 2	23 1	25.1	27 0	28.9	30 9	32 8	34.8
8.0	14 2	16.0	17.8	19 5	21 3	23.1	24 8	26 7	28 4	30 2	32.0
8.5	13.4	15.2	16.9	18.5	20.2	21.9	23.6	25.2	26 9	28.6	30.3
9.0	12 9	14 6	16 2	17 8	19 4	21 1	22 7	24 3	25 9	27 6	28.2
9 5	12 2	13.8	15 3	16 8	18 3	19 8	21 4	22 9	24 4	26 0	27 5
10.0	11 7	13.2	14 7	16 1	17 6	19 1	20 5	22 0	23.4	24.9	27.9
10 5	11 2	12.6	14 0	15 4	16 8	18 2	19 6	21 0	22.4	23.8	25.2
11 0	10 7	12.1	13.4	14 7	16 0	17.4	18 7	20.0	21 4	22.8	24.1
11.5	10.2	11 5	12.8	14 1	15 4	16.7	18 0	19 3	20 6	21 8	23.1
12.0	9 8	11 1	12.3	13 5	14.7	15.9	17.2	18 4	19 6	20 9	22.1

**Table 12-5. Field Check: Dry Flue-gas Loss, Natural Gas**

(Per cent, based on 1,050 Btu/cu ft)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room										
	400	450	500	550	600	650	700	750	800	850	900
3.0	25.2	28.3	31.4	34.6	37.7	40.8	43.9	47.1	50.3	53.4	56.6
4.0	19.2	21.6	24.0	26.4	28.8	31.2	33.6	36.0	38.4	40.8	43.2
5.0	15.3	17.2	19.1	21.0	22.9	24.8	26.7	28.6	30.6	32.5	34.4
5.5	13.9	15.7	17.4	19.1	20.8	22.6	24.3	26.1	27.8	29.5	31.2
6.0	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8
6.5	11.8	13.3	14.7	16.2	17.7	19.2	20.7	22.2	23.6	25.1	26.6
7.0	11.0	12.3	13.7	15.1	16.5	17.8	19.2	20.6	21.9	23.3	24.7
7.5	10.2	11.5	12.8	14.1	15.4	16.7	17.9	19.2	20.5	21.8	23.1
8.0	9.5	10.7	11.9	13.1	14.3	15.4	16.6	17.8	19.0	20.2	20.4
8.5	9.0	10.1	11.2	12.3	13.4	14.5	15.7	16.8	17.9	19.0	20.2
9.0	8.5	9.6	10.6	11.7	12.8	13.8	14.9	16.0	17.1	18.2	19.3

**Table 12-6. Field Check: Dry Flue-gas Loss, Water Gas**  
(Per cent, based on 530 Btu/cu ft)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room										
	400	450	500	550	600	650	700	750	800	850	900
3 0	33 4	37 5	41.6	45.7	50.0	54.1	58.2	62 3	66.5	70 7	74 8
4.0	25 4	28 5	31 7	34 9	38.1	41.2	44 4	47 5	50 7	53 8	57.0
5 0	20 4	23 0	25 6	28 2	30 8	33.3	35 8	38 3	40 9	43 5	46 0
5 5	18 6	21.0	23 3	25.6	28 0	30 3	32 6	34 9	37 2	39 6	41 9
6 0	17.2	19.3	21.5	23.7	25.9	28.0	30.2	32 3	34 4	36 6	38 6
6.5	15 9	17 9	19 0	21 9	23 9	25 9	27 9	29.9	31 9	33 9	35.9
7 0	14 8	16 7	18 6	20 5	22 3	24 1	26 0	27.8	29 7	31 6	33 5
7 5	13 9	15 7	17.5	19 2	20 9	22 6	24 4	26 2	27 9	29 7	31 5
8 0	13 2	14 9	16 5	18 1	19 8	21 4	23 1	24 7	26 3	28 0	29 6
8 5	12.3	13.8	15.4	17.0	18.5	20.0	21.5	23 0	24.6	26.1	27.7
9 0	11 6	13 1	14 5	15 9	17 4	18 8	19.3	21 7	23.1	24 6	26.1
9 5	11 0	12 4	13 8	15 2	16 6	18 0	19.4	20 7	22.1	23 5	24.8
10 0	10 5	11 8	13 1	14 4	15 8	17 1	18.4	19 7	21.0	22 3	23.6
10 5	9 9	11 2	12 5	13 7	15.0	16 2	17.4	18 6	19 9	21 2	22 4
11.0	9 6	10 8	12.0	13 2	14 4	15 6	16.8	18 0	19.4	20 5	21 6
11 5	9.2	10 4	11 5	12 7	13 8	15 0	16 1	17 3	18.4	19 6	20.7
12 0	8 9	10 1	11 1	12 2	13.3	14 4	15 5	16 6	17.7	18.8	19.9
12 5	8 5	9 6	10 6	11 7	12 8	13 8	14 9	15 9	17 0	18.1	19.1
13 0	8 3	9 4	10 4	11 4	12 5	13 5	14 6	15 6	16 6	17 7	18.7

**Table 12-7. Field Check: Dry Flue-gas Loss, Propane**  
(Per cent, based on 2,500 Btu/cu ft)

CO <sub>2</sub> , per cent	Stack temp, deg F, above boiler room										
	400	450	500	550	600	650	700	750	800	850	900
3.0	34 9	39 2	43 5	48 0	52 3	56 6	61 1	65.4	69.7	74 1	78.5
4.0	26 5	29 8	33 2	36 5	39 7	43 0	46.3	49 6	52.9	56.2	59.5
5.0	21.5	24 2	26 8	29.5	32 2	34.9	37 6	40.3	43.0	45.6	48.3
5 5	19.6	22.0	24.5	26 9	29 3	31 7	34 2	36.7	39.1	41.6	44.0
6.0	17.7	19.9	22.1	24.2	26.4	28.6	30.8	33.0	35.2	37.4	38.6
6.5	16.5	18 6	20.7	22.7	24 7	26 8	28.9	30.9	33.0	35.1	37.1
7.0	15.4	17 3	19.2	21.1	23.0	24 9	26 9	28.8	30.7	32.6	34.5
7.5	14 2	16.0	17.8	19 5	21 3	23.1	24 9	26.6	28.4	30.2	31 9
8 0	13 4	15 1	16 8	18 4	20 1	21 8	23 5	25.2	26.9	28.6	30 3
8 5	12.7	14 3	15.9	17.5	19.0	20 6	22.2	23.7	25.3	26.9	28.5
9 0	11 9	13 4	14 9	16 4	17.8	19 3	20 8	22.3	23.8	25.3	26.8



Table 12-8. Field Check: Per cent Hydrogen Loss, Gaseous Fuels

Gas	Btu/ cu ft	Lb water /cu ft gas	Per cent hydrogen loss											
			Stack temp, deg F, above boiler room											
			400	450	500	550	600	650	700	750	800	850	900	
Natural gas.....	1,050	0.0982	11.5	11 7	12.0	12.2	12 4	12.6	12.8	13.0	13.2	13.4	13 7	
Mixed, natural and water gas..	525	0.0479	11.4	11 6	11.8	12.0	12 2	12.5	12.7	13.0	13.2	13.4	13 7	
Retort coal gas.....	558	0.0564	12.2	12 5	12.7	12.9	13.1	13 3	13.6	13.8	14.0	14 3	14 5	
Mixed coke-oven and carbu- reted water gas . . . .	545	0.0494	11.2	11.4	11 6	11.8	12.1	12 3	12.5	12.7	12 9	13 2	13 4	
Carbureted water gas. . . .	545	0.0385	8 6	8 8	9 0	9 2	9 3	9.5	9.7	9.9	10 0	10 1	10 3	
Water gas (coke) . . . .	287	0.0252	10 8	11.1	11.3	11.5	11.6	11 8	12.0	12.2	12.4	12 6	12 8	
Water gas (bituminous) . . .	261	0.0223	10 3	10 5	10 7	10 9	11 1	11 3	11 5	11 7	11 9	12 1	12 3	
Oil gas (Pacific Coast) . . .	551	0.0545	12.1	12.2	12.6	12 8	13.0	13 2	13 4	13.6	13.9	14 2	14.5	
Producer gas (buckwheat an- thracite) . . . .	143	0.0104	9 0	9.2	9 4	9 6	9 8	10 0	10 2	10 5	10 7	10 9	11 2	
Blast-furnace gas . . . .	92	0.0009	1 2	1 2	1 2	1 3	1 3	1 3	1 3	1 4	1 4	1 4	1 4	
Butane . . . . .	3,225	0.1865	7.0	7.2	7 3	7 5	7 7	7 8	7 9	8.1	8.2	8 4	8 5	
Propane . . . . .	2,572	0.1425	6 9	7.1	7.3	7.4	7.6	7.8	7 9	8.1	8.2	8 4	8 5	

NOTE: For analysis of the gases shown above, see Table 9-5.

Table 12-9. Field Check: Per Cent Hydrogen Loss, Liquid and Solid Fuels

Fuel	Btu/lb	H <sub>2</sub> , per cent	Stack temp, deg F, above boiler room										
			400	450	500	550	600	650	700	750	800	850	900
No. 6 fuel oil	18,500	10 8	6 5	6 6	6 7	6 8	6 9	7 0	7 2	7 3	7 4	7 5	7 7
No. 2 fuel oil	19,300	12 2	7 0	7 1	7 3	7 4	7 5	7 6	7 8	7 9	8 1	8 3	8 4
Anthracite . .	13,000	1 8	1 5	1 5	1 6	1 6	1 7	1 7	1 7	1 8	1 8	1 9	1 9
Bituminous . .	14,000	4 2	3 0	3 1	3 2	3 3	3 4	3.5	3.6	3.7	3 8	3.9	4 0

**Computation of Moisture from Hydrogen Loss.** As most fuel analyses used commercially are of the "proximate" type and do not include the per cent of hydrogen, it is frequently necessary to estimate or assume hydrogen content before computing this loss. This may be accomplished in at least three ways:

1. A number of tables in this volume include either typical percentages of hydrogen for the various fuels or show the amount of water vapor produced by the combustion. Included are Tables 12-8 (gas), 12-9 (liquid and solids), 9-5 (gas), and various tables under discussions of the individual fuels.

2. For *coal*, Fieldner and Selvig describe a simple method for computing the approximate hydrogen from the proximate analysis. This will be found as Fig. 11-15 and its accompanying material.

3. For *oil*, Todd describes a method of determining approximate hydrogen from specific gravity. This is shown in Fig. 11-17.

## METHOD 2. NOMOGRAPH METHOD OF COMPUTING HEAT BALANCES

The following, or nomograph, method of computing heat balance is more accurate than the chart method. In fact, it will be found adequate for most use, excepting where extreme accuracy is required or for unusual ultimate analyses which would be out of line with the assumptions upon which these alignment charts were based.

### Heat Balance from Nomographs:

1. Find the dry flue-gas loss from the figure corresponding to the fuel used (Fig. 12-1 to 12-16).

2. Find the hydrogen loss from Fig. 12-17 (weight basis), or Fig. 12-18 (volume basis). Hydrogen ranges for the several fuels are shown as Table 12-10. Where the proximate but not the ultimate analysis of coal is known, the hydrogen content may be approximated by the method devised by Fieldner and Selvig and described in Chap. 11 (page 366).

3. Find the moisture in the fuel loss from Fig. 12-19.

4. Find the moisture in the air loss from Figs. 12-20 and 12-21.

5. Find the unconsumed carbon in the flue-gas loss (CO loss) from Fig. 12-22.

6. Find the unconsumed carbon in the refuse loss (ash loss) from Fig. 12-23.

7. Find the radiation loss from Fig. 12-24.

8. Where the boiler output can be calculated from the steam flow the sum of items 1 to 7 in Btu plus the Btu output per unit of fuel should equal the heat in the fuel unit.

Where the output is not known and cannot be readily measured, the heat in a unit of fuel minus the sum of these losses expressed in Btu per unit of fuel should equal the heat in the steam per unit of fuel.

All such figures can be readily converted to percentage results.

**Table 12-10. Range of Hydrogen Per Cent, Pounds of Air, and CO<sub>2</sub> Per Cent for Zero Excess Air for Typical Solid and Liquid Fuels<sup>1</sup>**

Fuel	Range of per cent hydrogen	Range of lb of atmospheric air at zero excess air per 10,000 Btu	Range of CO <sub>2</sub> per cent at zero excess air
Anthracite . . . . .	1 8-2 9	7.81-7 93	19 3-20 0
Semianthracite . . . . .	3 2-3 4	7 68-7 82	19.1-19.2
Low-volatile bituminous . . . . .	3 9-4 5	7.62-7 73	18 5-18 8
Medium-volatile bituminous . . . . .	4 7	7 77	18 5
High-volatile bituminous A . . . . .	4 6-5 9	7 51-7 73	17.7-18 7
High-volatile bituminous B . . . . .	4 2-5 0	7 56-7 73	18 0-18 7
High-volatile bituminous C . . . . .	4.0-4 6	7 54-7 67	18 0-18 7
Subbituminous . . . . .	3 8	7 56-7 57	19 1-19 2
Lignite . . . . .	2 8-3 1	7 47-7 52	19 2-19 5
Coke . . . . .	0 5-3 2	7 63-8 13	19 3-20 7
Softwoods . . . . .	5 8-7 02	7 05-7 22	18.7-20 4
Hardwoods . . . . .	6 02-6 93	7 09-7 28	19 5-20.5
Bagasse . . . . .	5.89-6 56	6.25-6.99	19 4-21.0
60° API gasoline . . . . .	14 8	7 46	14 87
45° API kerosene . . . . .	14 0	7 42	15 12
30° API gas oil . . . . .	12 8	7 45	15 48
15° API fuel oil . . . . .	11 5	7 58	15.90

NOTE: For gases, the usual ultimate analysis is not customarily made. The analysis is usually reported as the gaseous components, and hence the hydrogen content is not available. See Table 9-5, for the composition of the flue gas for the common fuels, in which the weight of water formed per cubic foot of gas burned is given.

<sup>1</sup> Compiled from "Combustion Engineering," pp. 25-3 to 25-13.

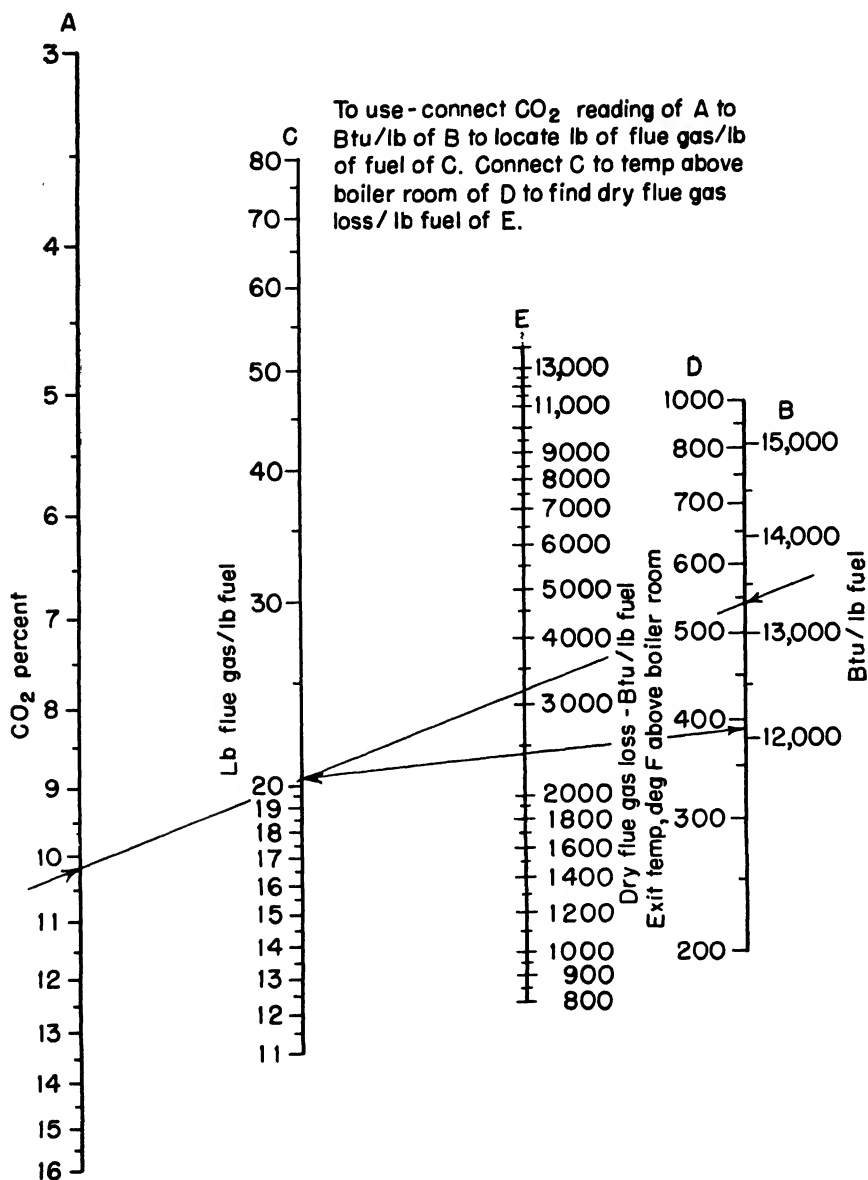


FIG. 12-1. Anthracite—dry flue-gas loss.

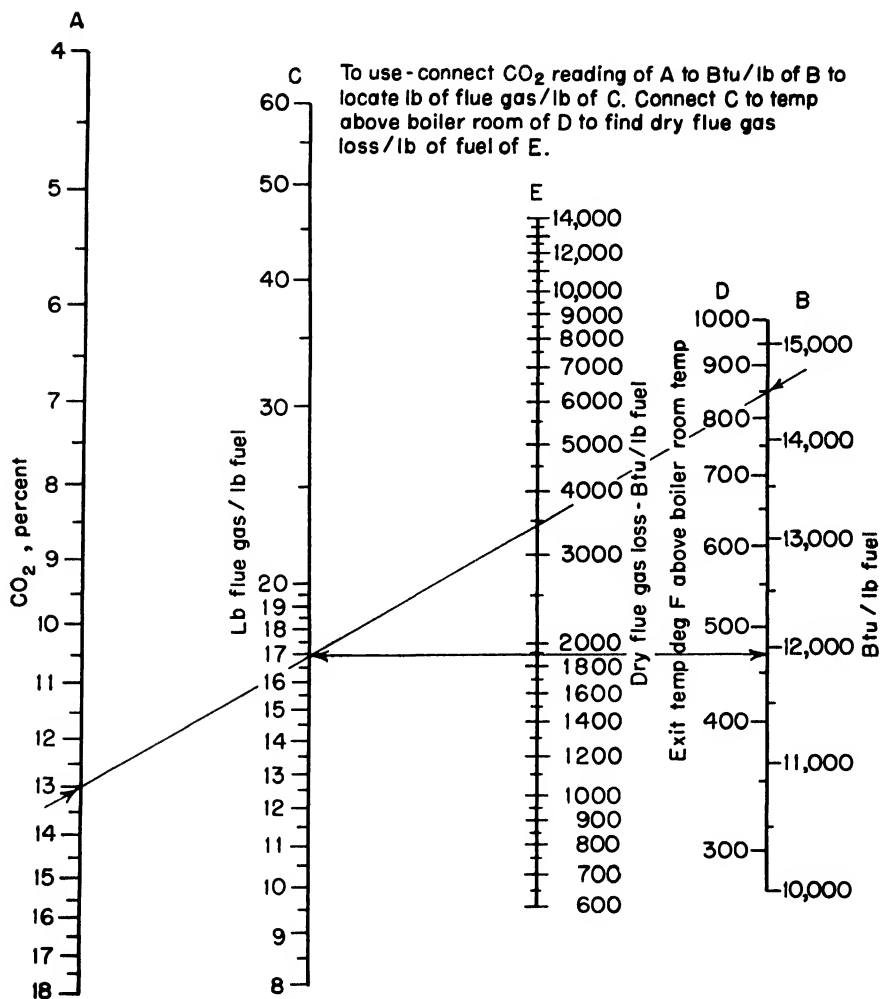


FIG. 12-2. Bituminous coal—dry flue-gas loss.

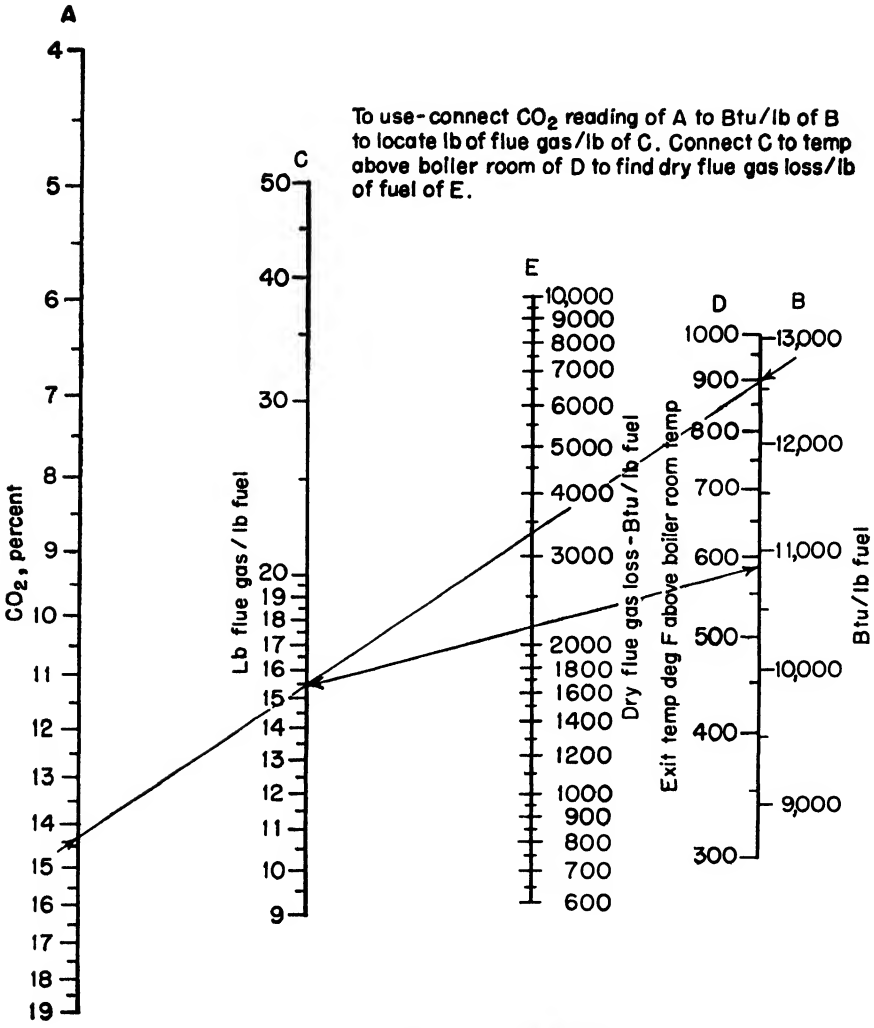


FIG. 12-3. Coke—dry flue-gas loss.

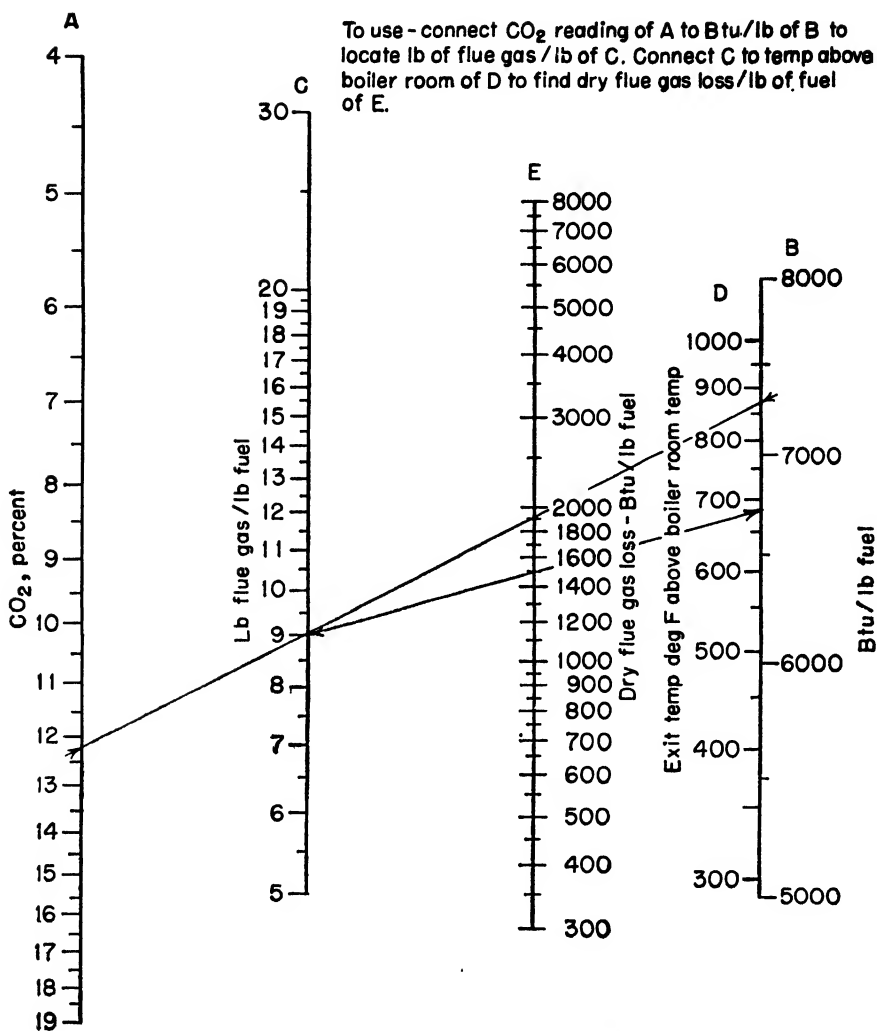


FIG. 12-4. Lignite—dry flue-gas loss.

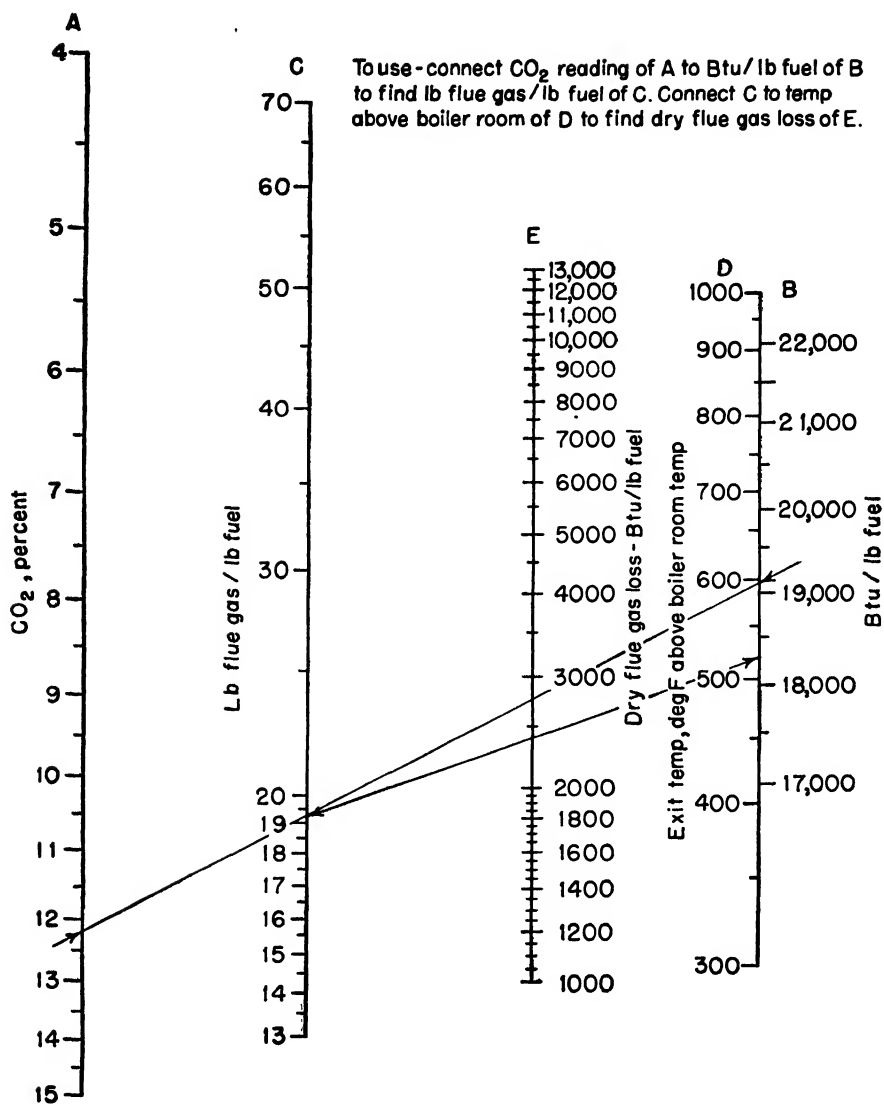


FIG. 12-5. Fuel oil—dry flue-gas loss.

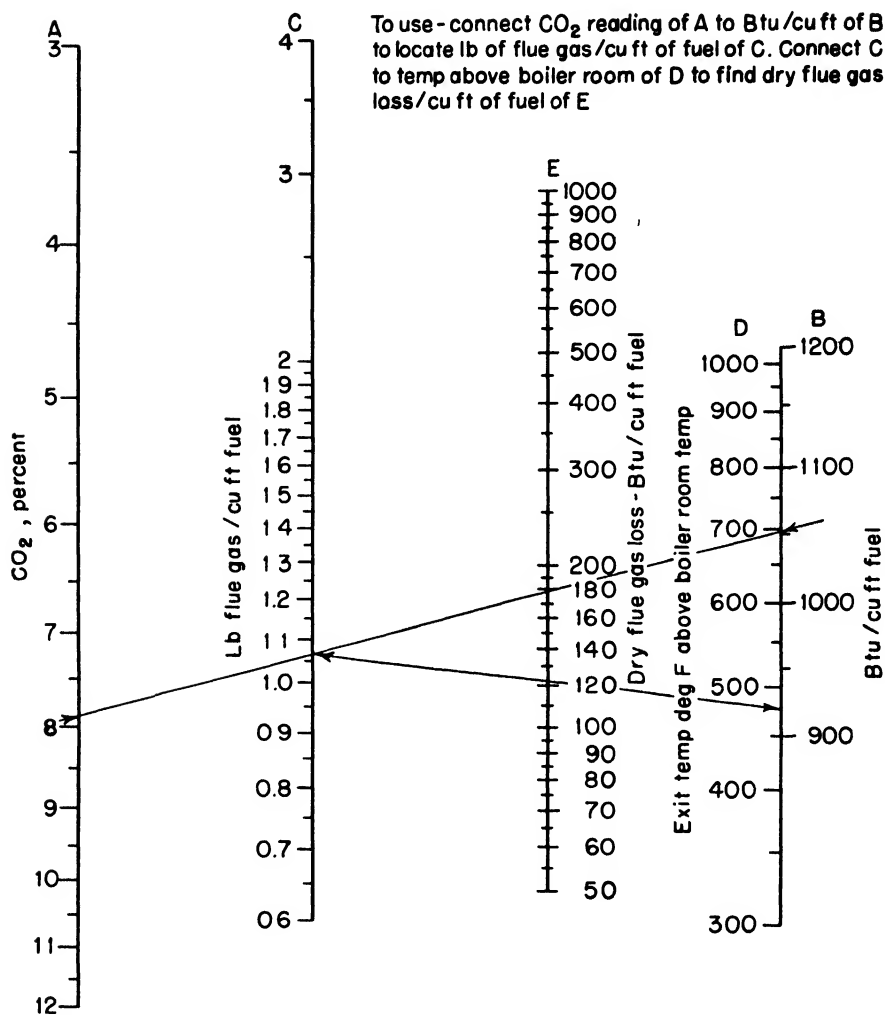


FIG. 12-6. Natural gas—dry flue-gas loss. Averaged analysis, see Table 9-5.



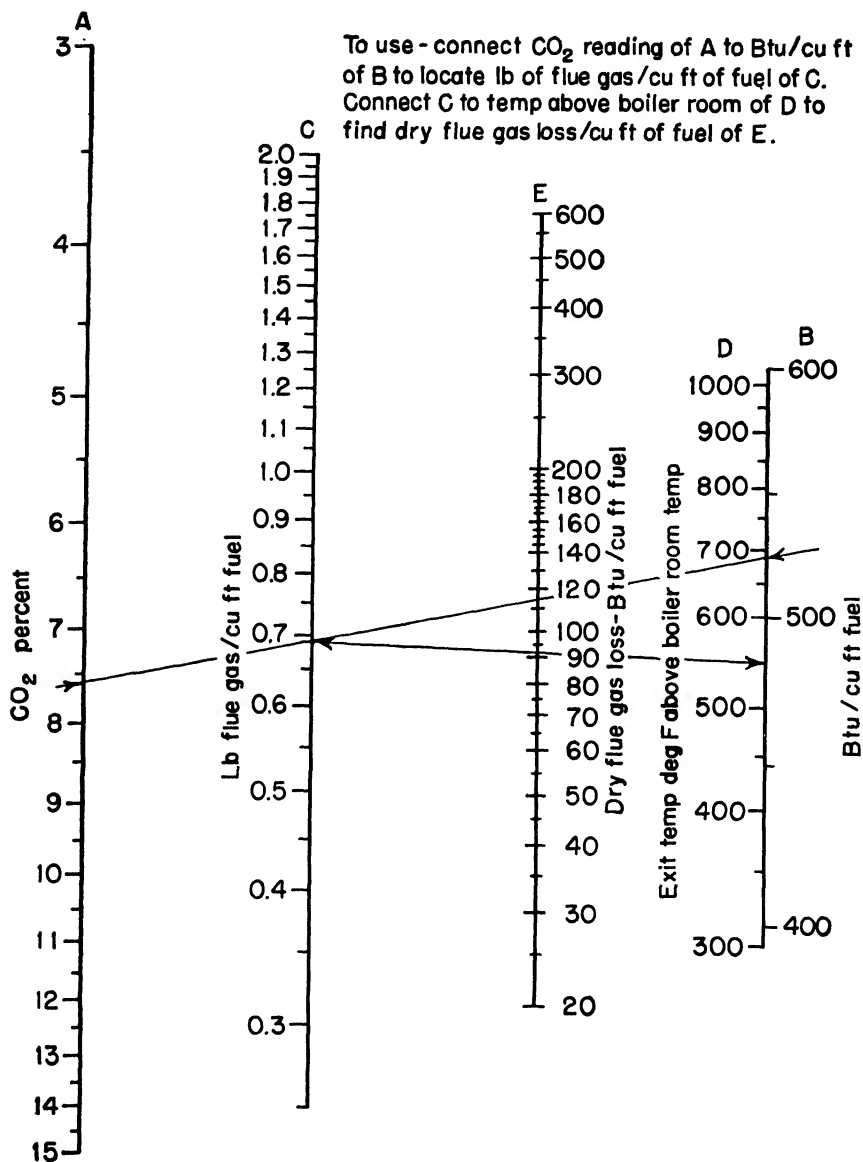


FIG. 12-7. Mixed natural gas and water gas—dry flue-gas loss. For analysis, see Table 9-5.

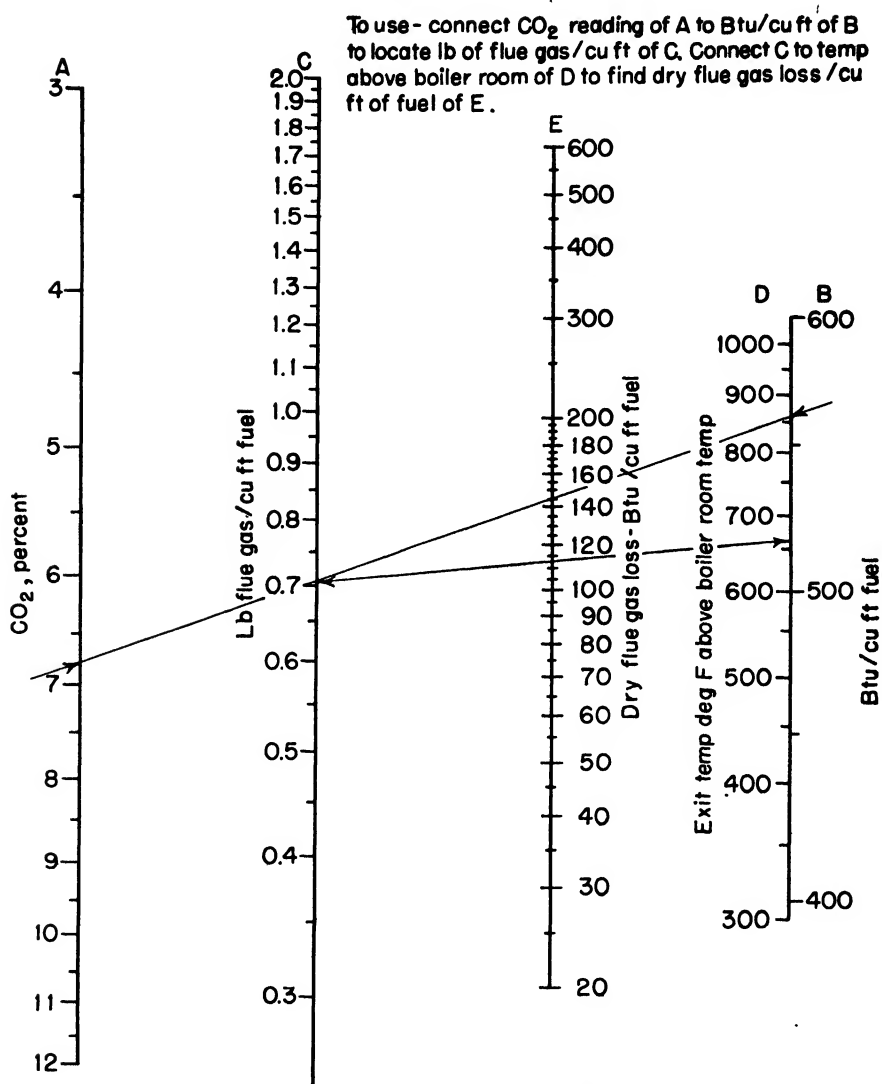


FIG. 12-8. Coal gas—dry flue-gas loss. Averaged analysis, see Table 9-5.

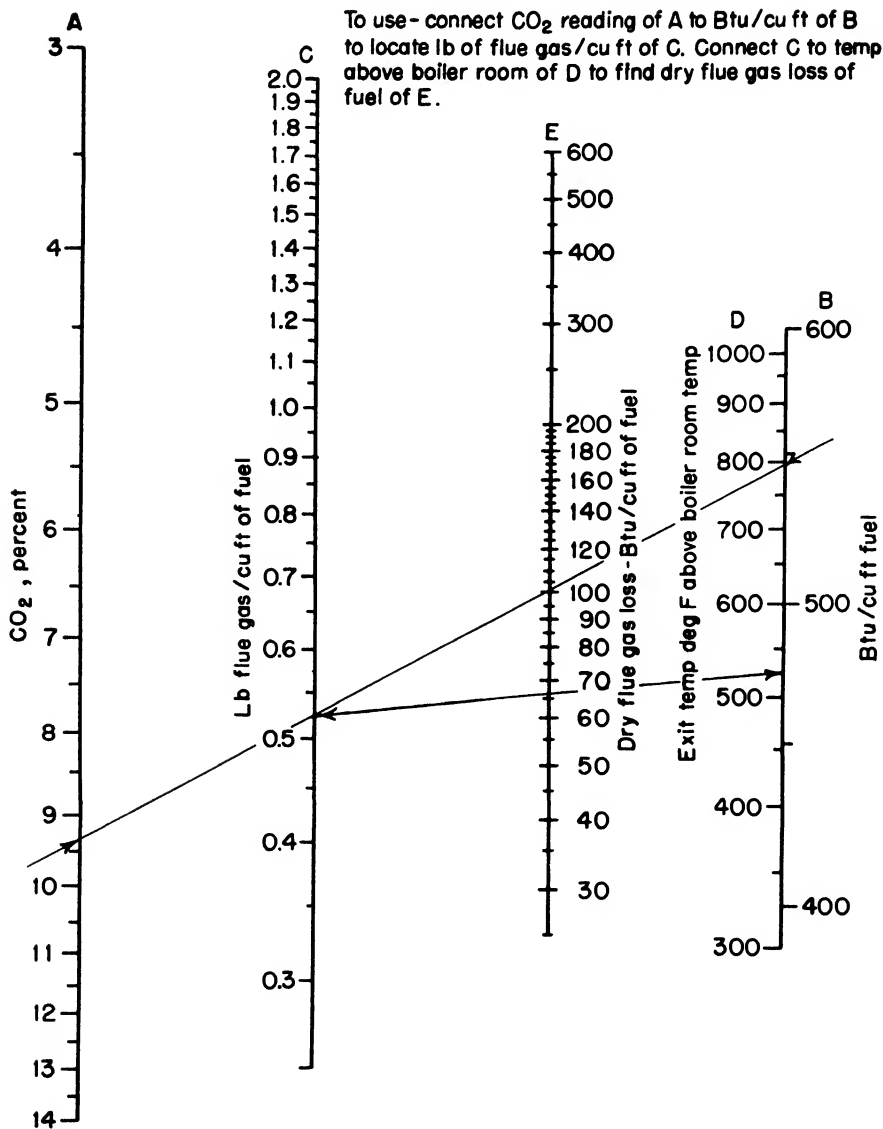


FIG. 12-9. Mixed coke oven and carburetted water gas—dry flue-gas loss. For analysis, see Table 9-5.

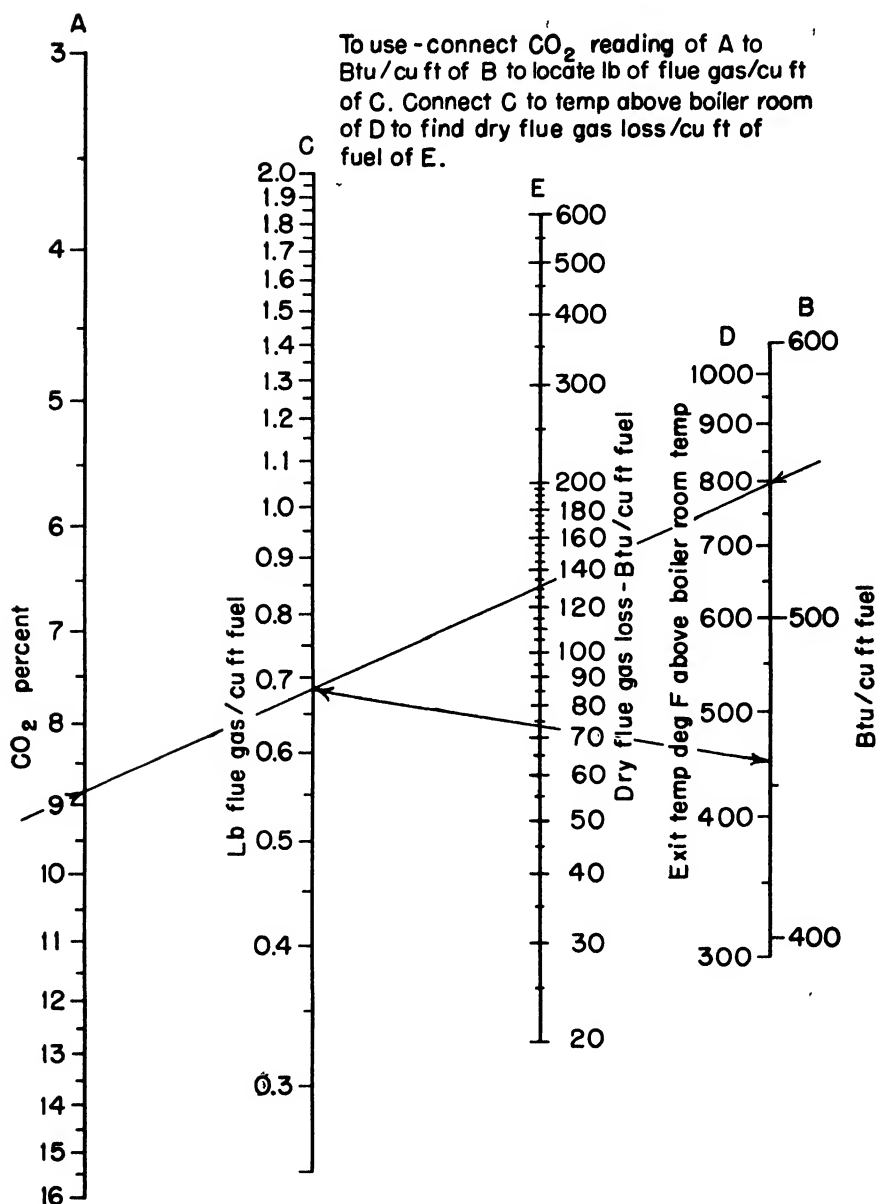


FIG. 12-10. Carbureted water gas--dry flue-gas loss. For analysis, see Table 9-5.

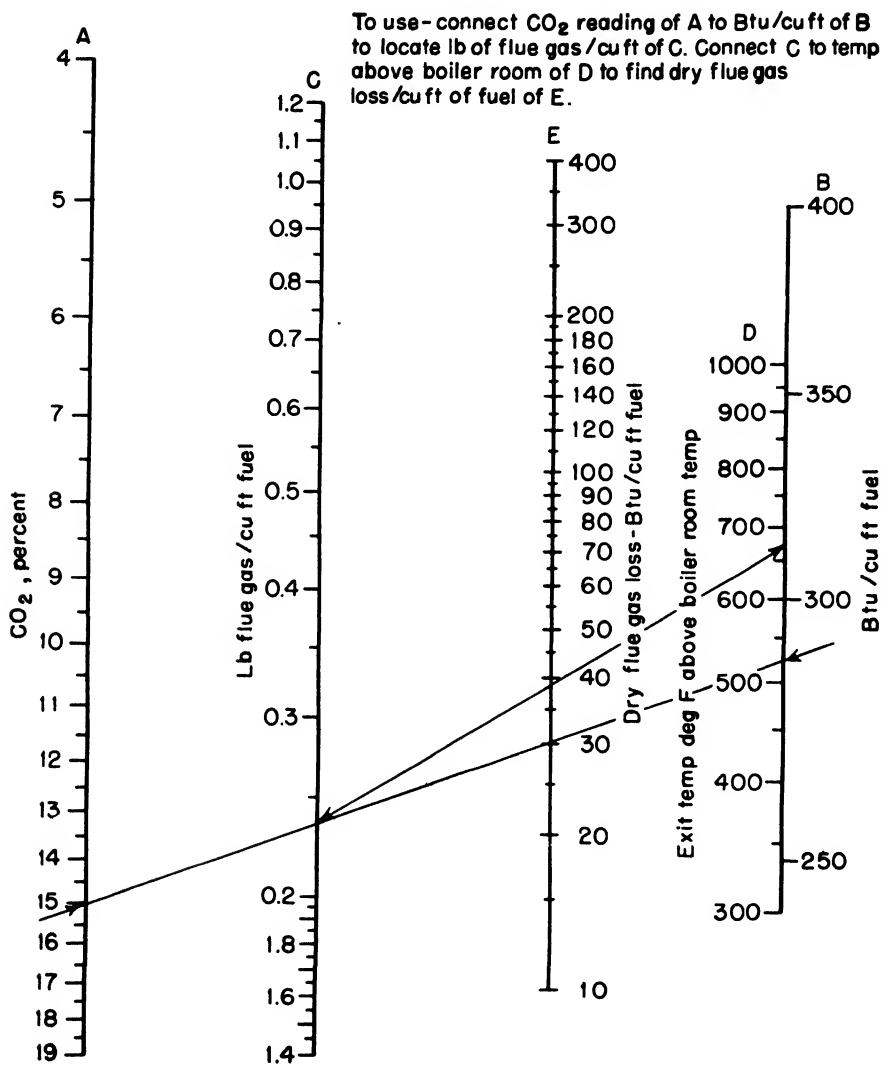


FIG. 12-11. Water gas (coke)—dry flue-gas loss. For analysis, see Table 9-5.

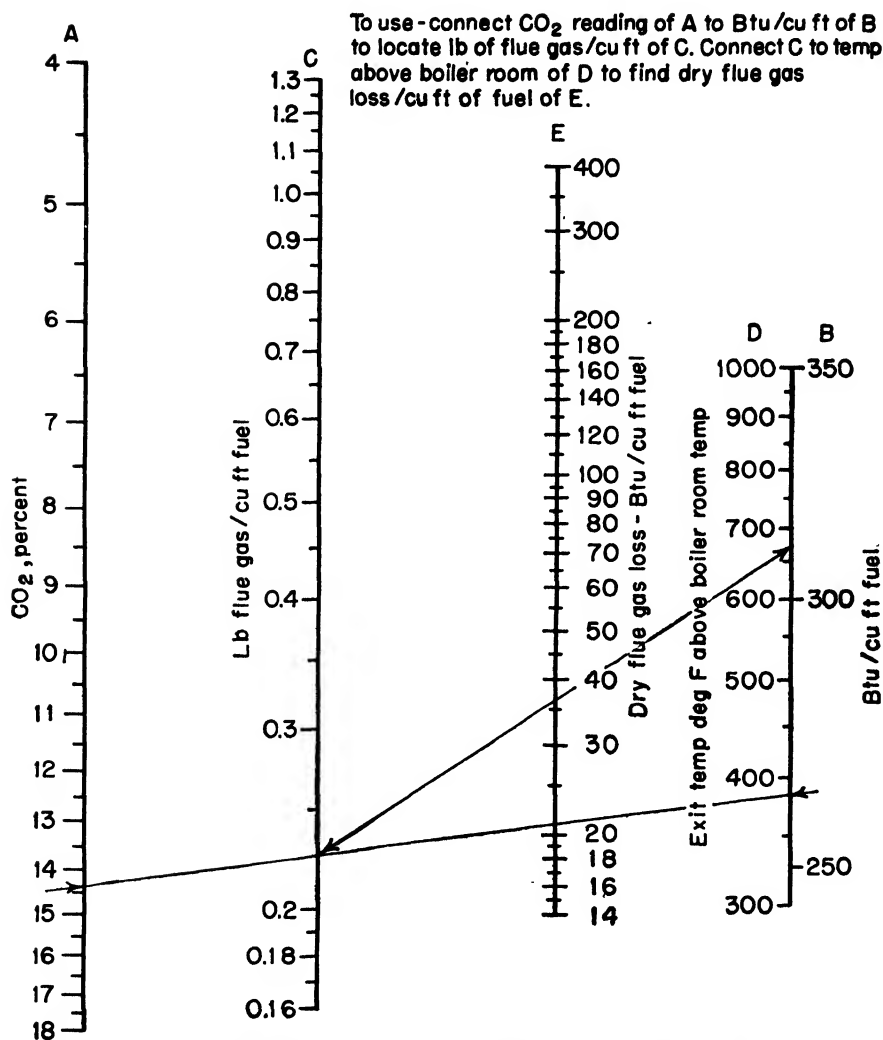


FIG. 12-12. Water gas (bituminous)—dry flue-gas loss. For analysis, see Table 9-5.

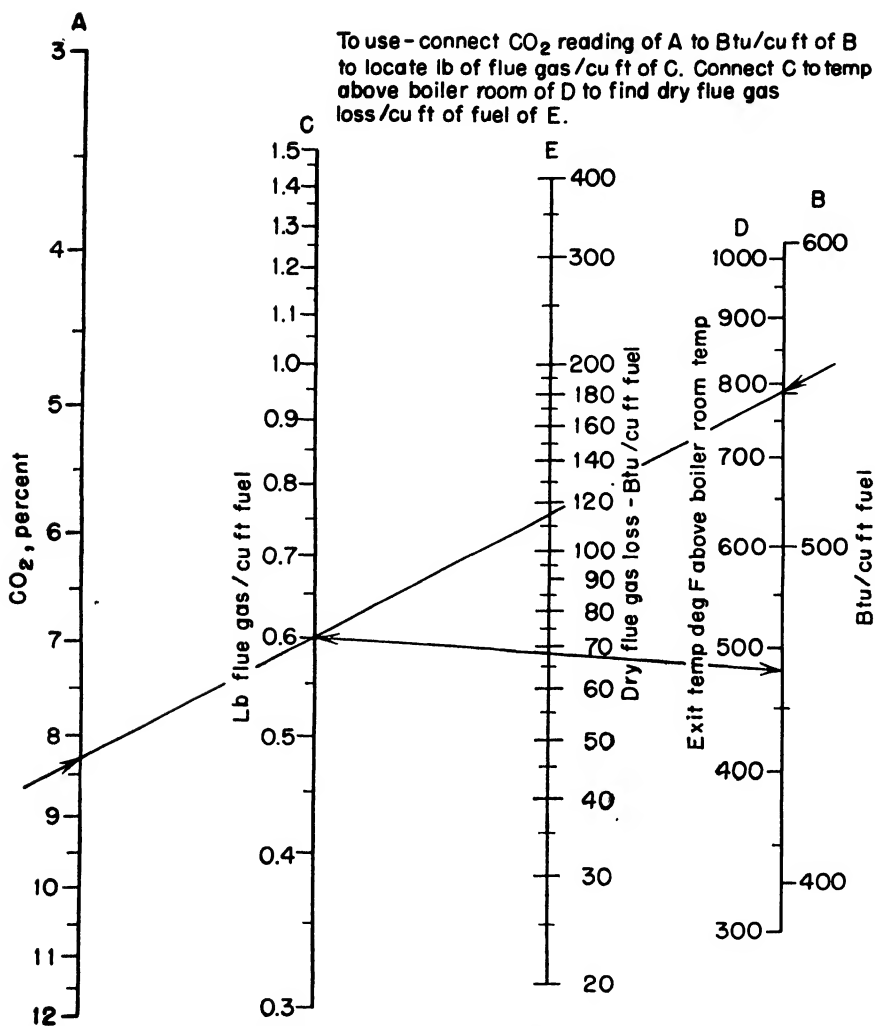


FIG. 12-13. Oil gas (Pacific Coast)—dry flue-gas loss. For analysis, see Table 9-5.

To use - connect  $\text{CO}_2$  reading of A to Btu/cu ft of B to locate lb of flue gas/cu ft of C. Connect C to temp above boiler room of D to find dry flue gas loss/cu ft of fuel of E.

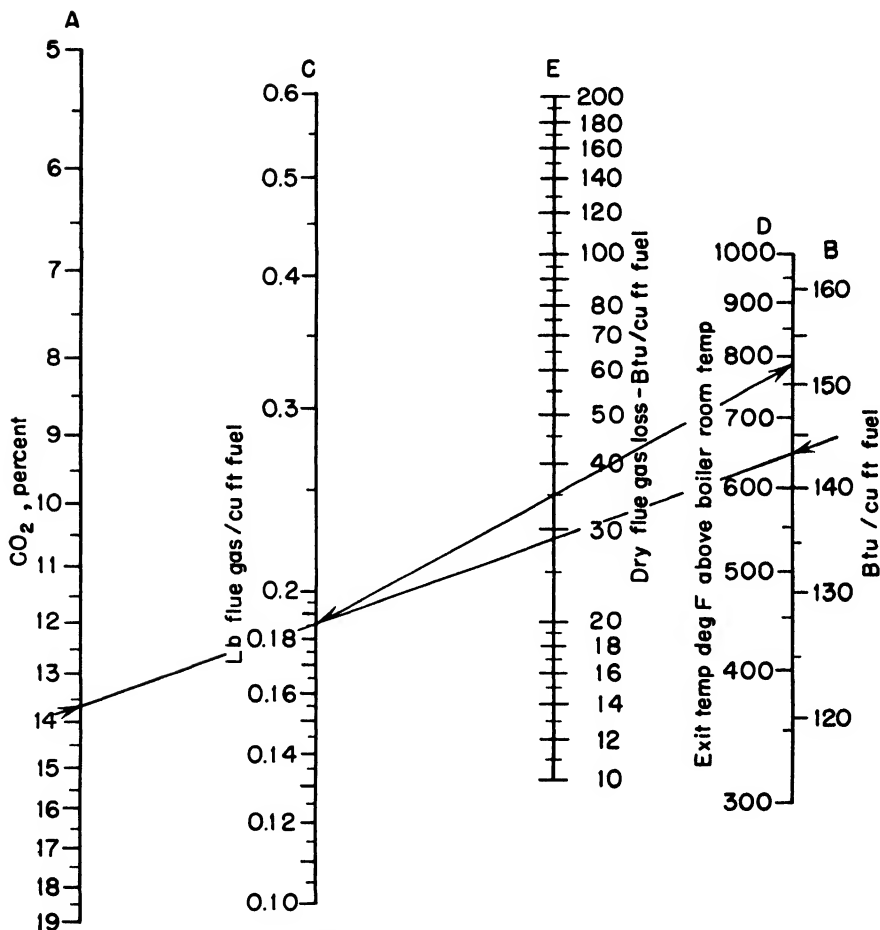


FIG. 12-14. Producer gas (buckwheat anthracite)—dry flue-gas loss. For analysis, see Table 9-5.



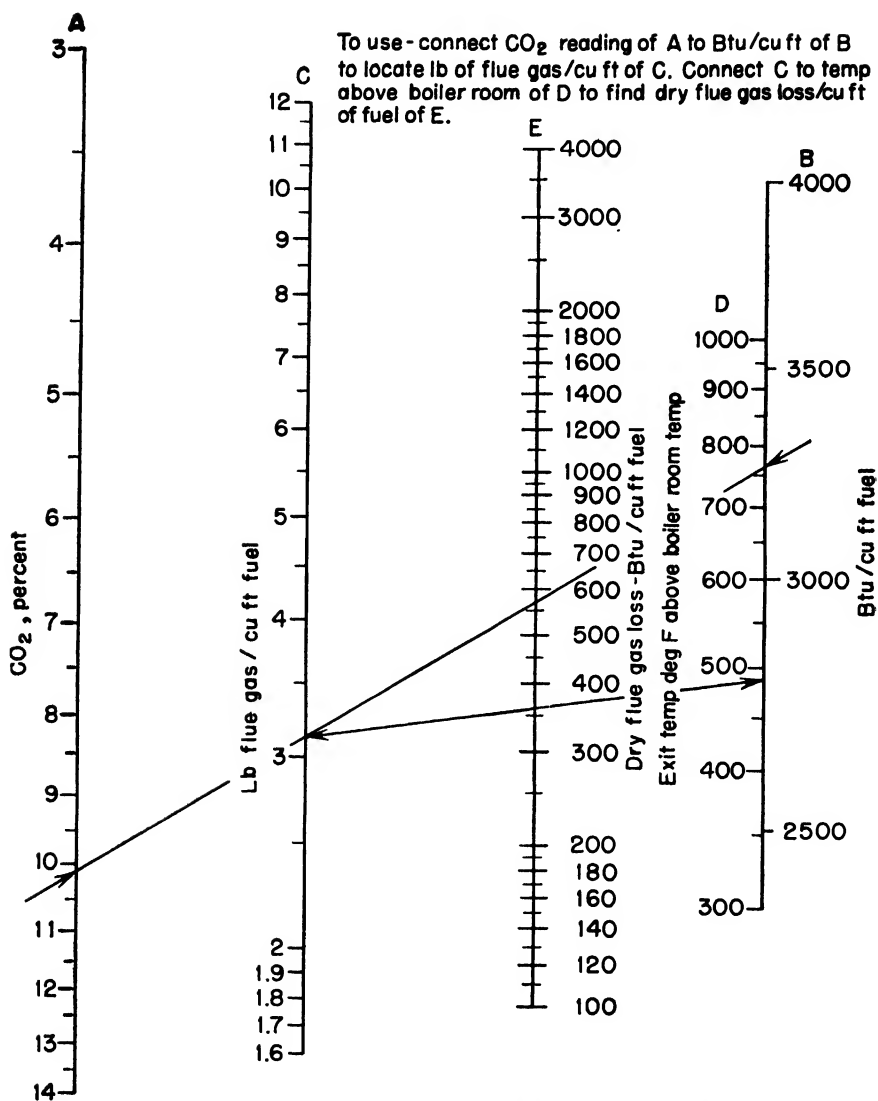


FIG. 12-15. Commercial butane—dry flue-gas loss. For analysis, see Table 9-5.

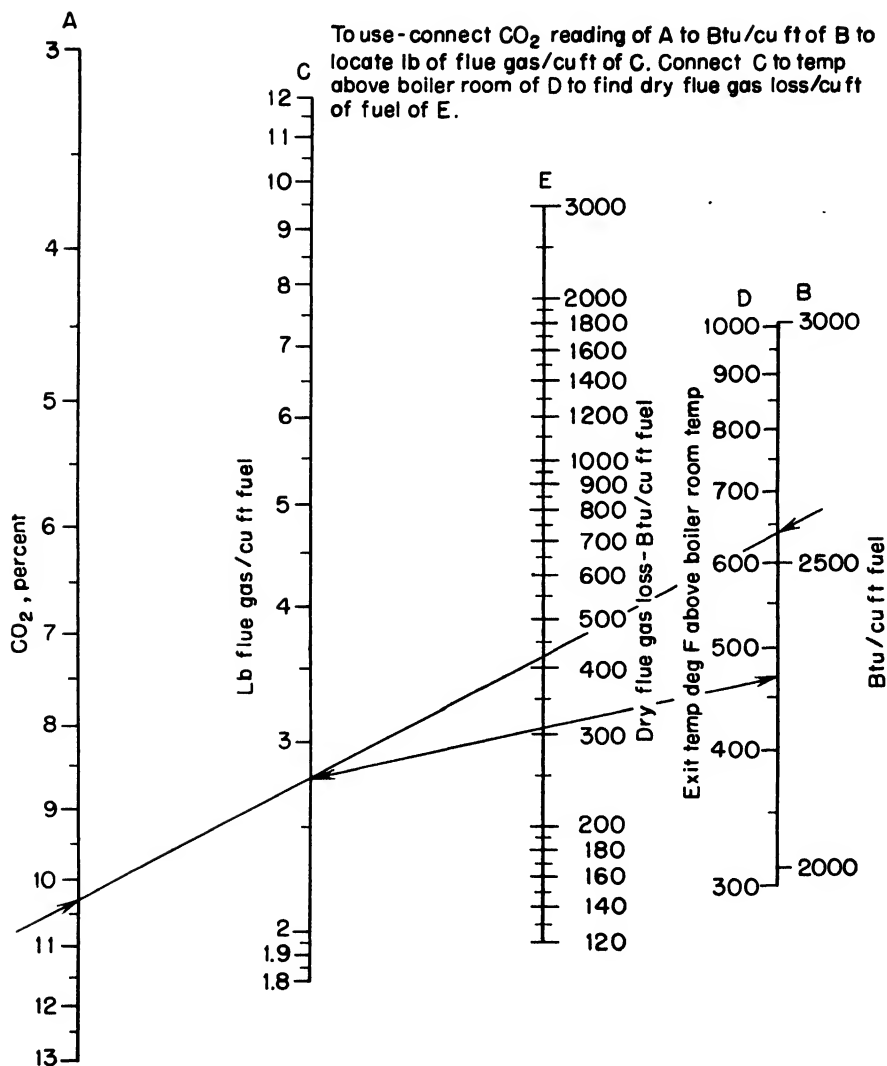


FIG. 12-16. Commercial propane—dry flue-gas loss. For analysis, see Table 9-5.

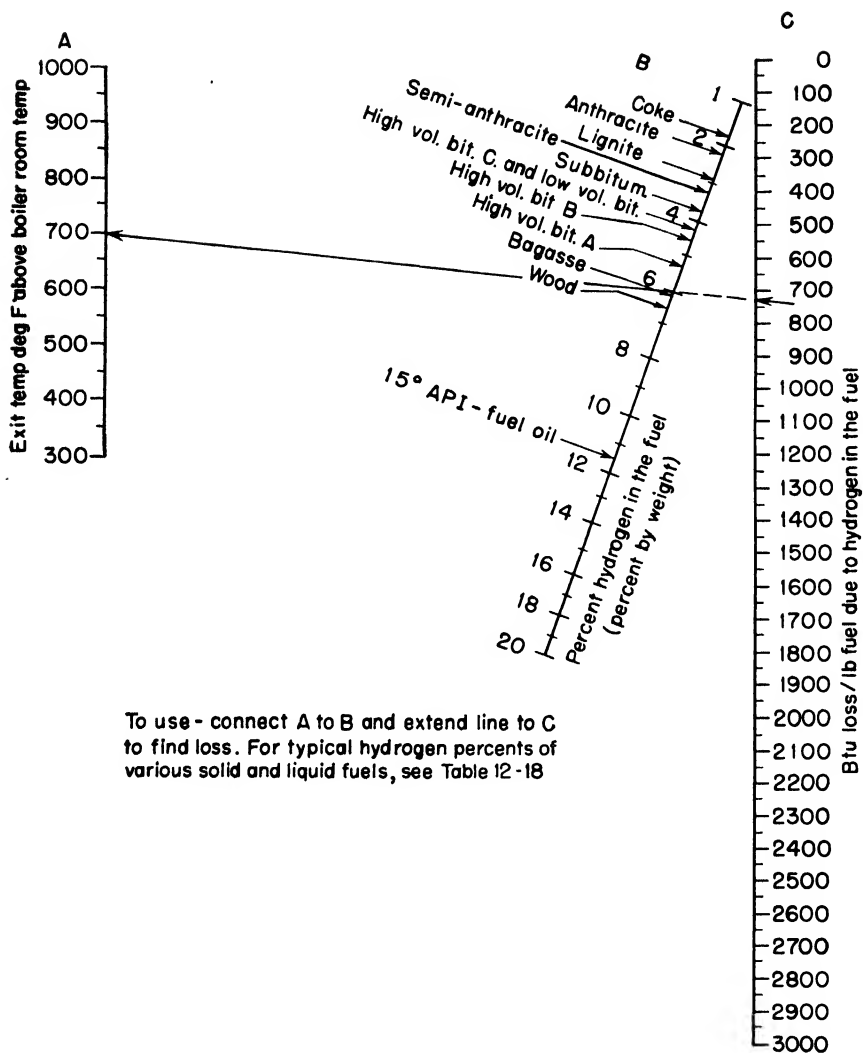


FIG. 12-17. Heat loss due to hydrogen in the fuel.

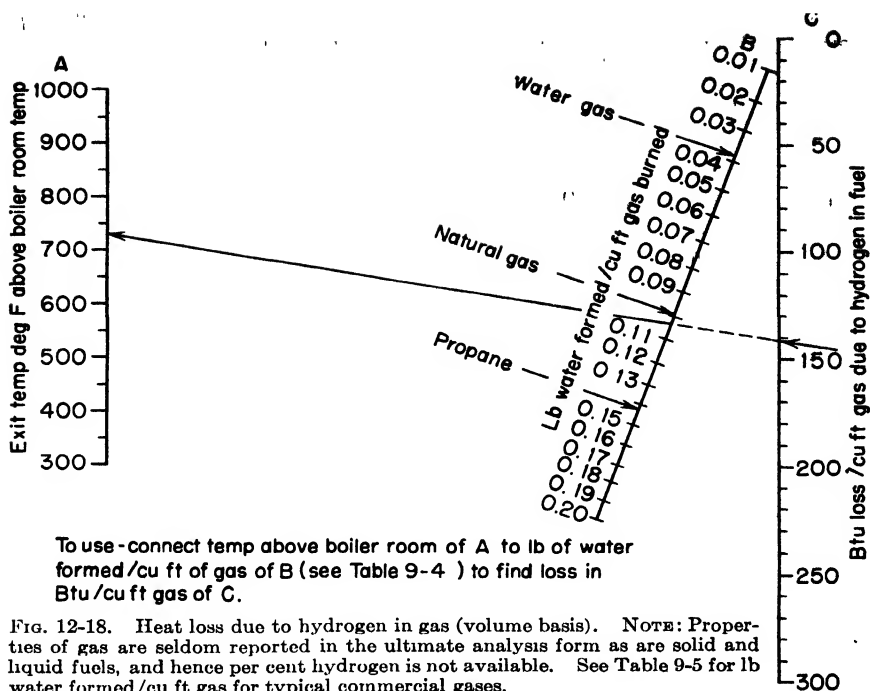


FIG. 12-18. Heat loss due to hydrogen in gas (volume basis). NOTE: Properties of gas are seldom reported in the ultimate analysis form as are solid and liquid fuels, and hence per cent hydrogen is not available. See Table 9-5 for lb water formed/cu ft gas for typical commercial gases.

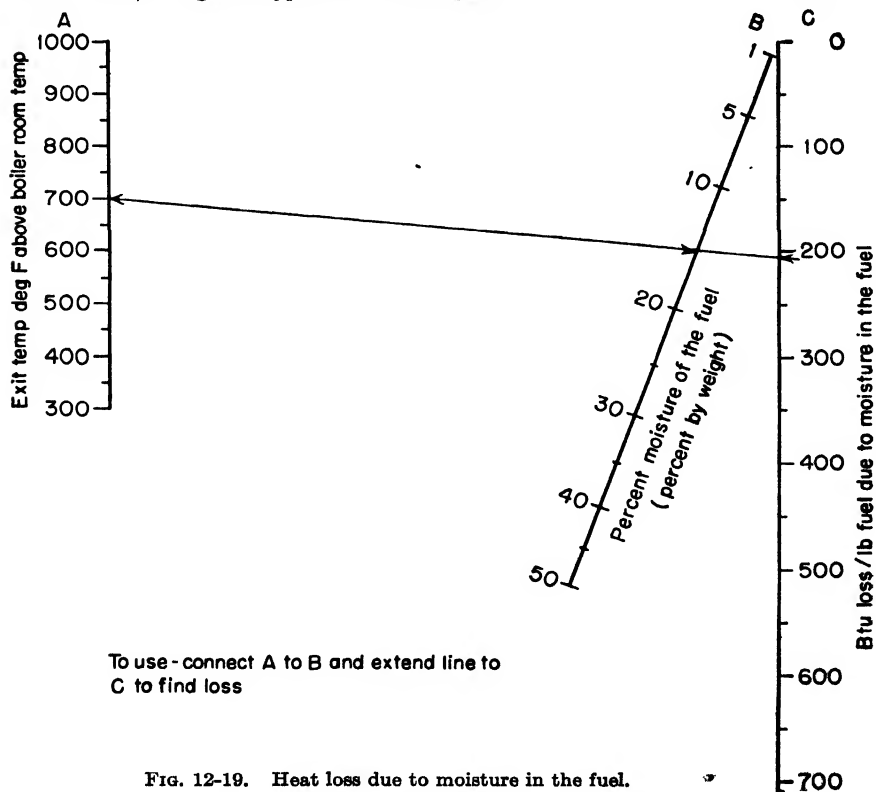


FIG. 12-19. Heat loss due to moisture in the fuel.

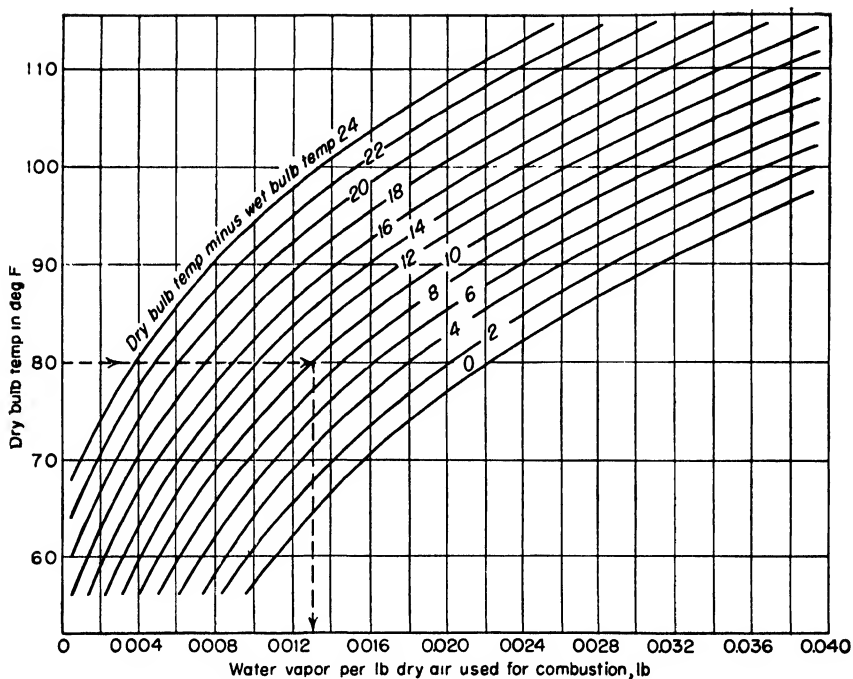


FIG. 12-20. Water vapor per pound of dry air used for combustion, pounds.

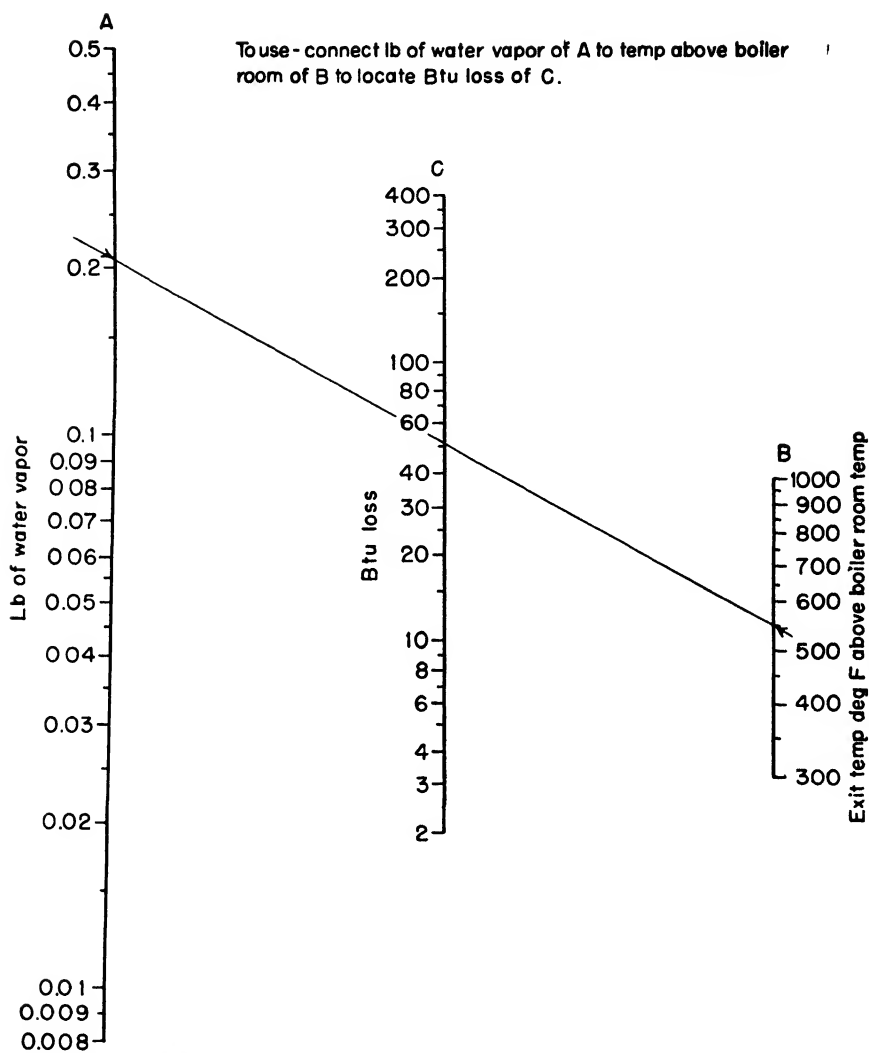


FIG. 12-21. Heat loss due to heating water vapor. NOTE: Since the water is already a vapor, the latent heat need not be taken into account, and the nomograph is based on the equation  $\text{Btu loss} = W_{\text{moisture}} \times 0.46(T_{\text{gas}} - T_{\text{air}})$ .

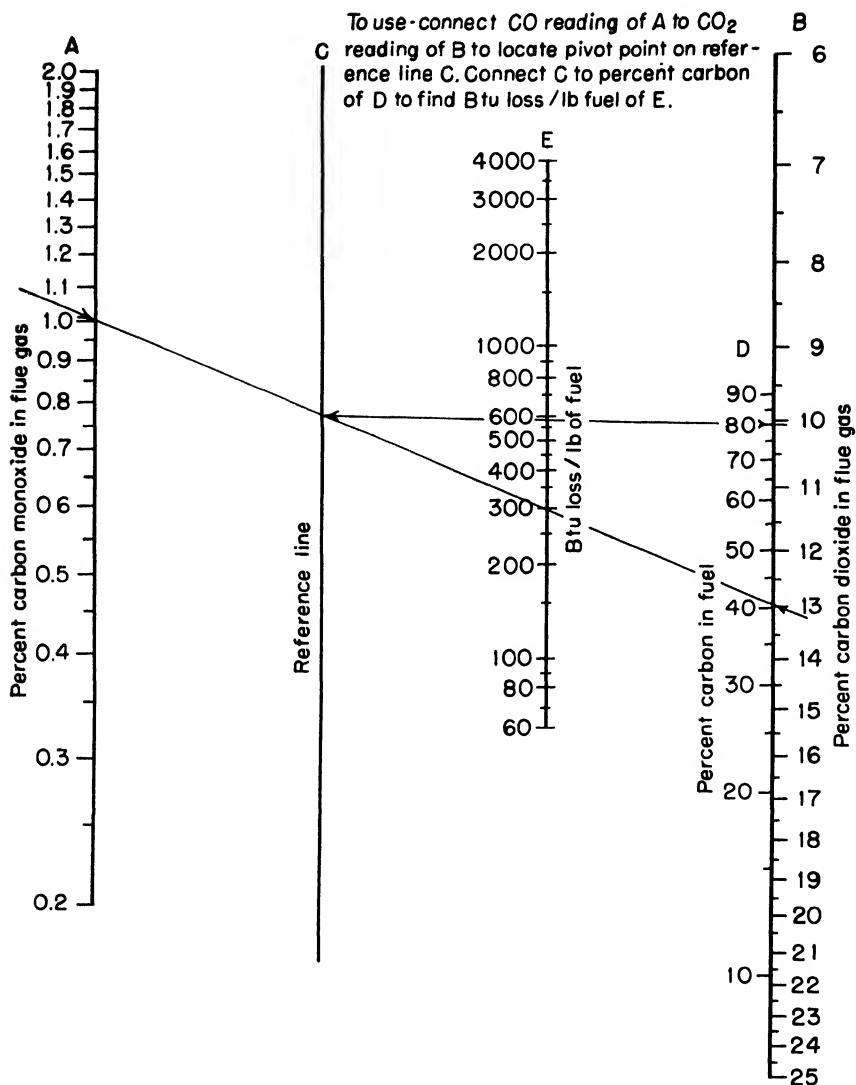


FIG. 12-22. Loss due to incomplete combustion of carbon as carbon monoxide in stack.

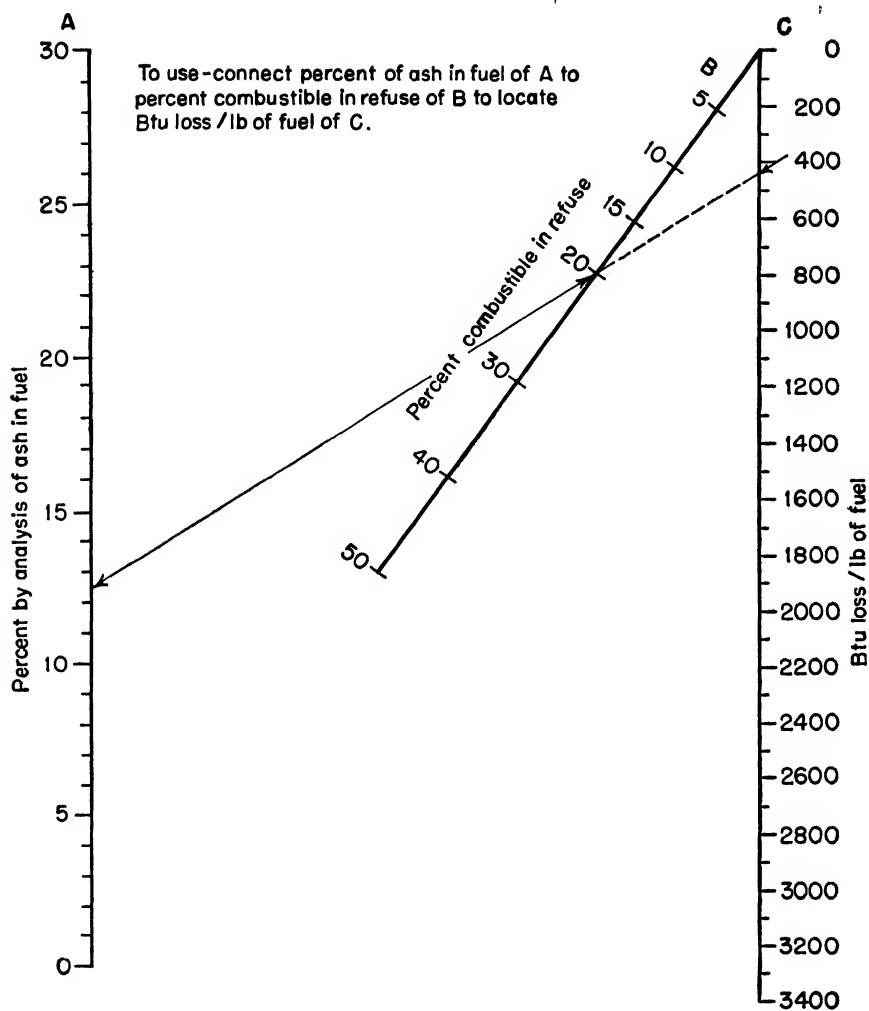


FIG. 12-23. Loss due to unconsumed carbon in the refuse.



A furnace wall must have at least one third its projected surface covered by water cooled surface before reduction in radiation loss is permitted

Air through air cooled walls must be used for combustion if reduction in radiation loss is to be made

Example: Unit guar for max cont capacity of 150,000 lb/hr with three water cooled walls  
Loss at 150,000 = 0.65 %  
Loss at 75,000 = 1.30 %

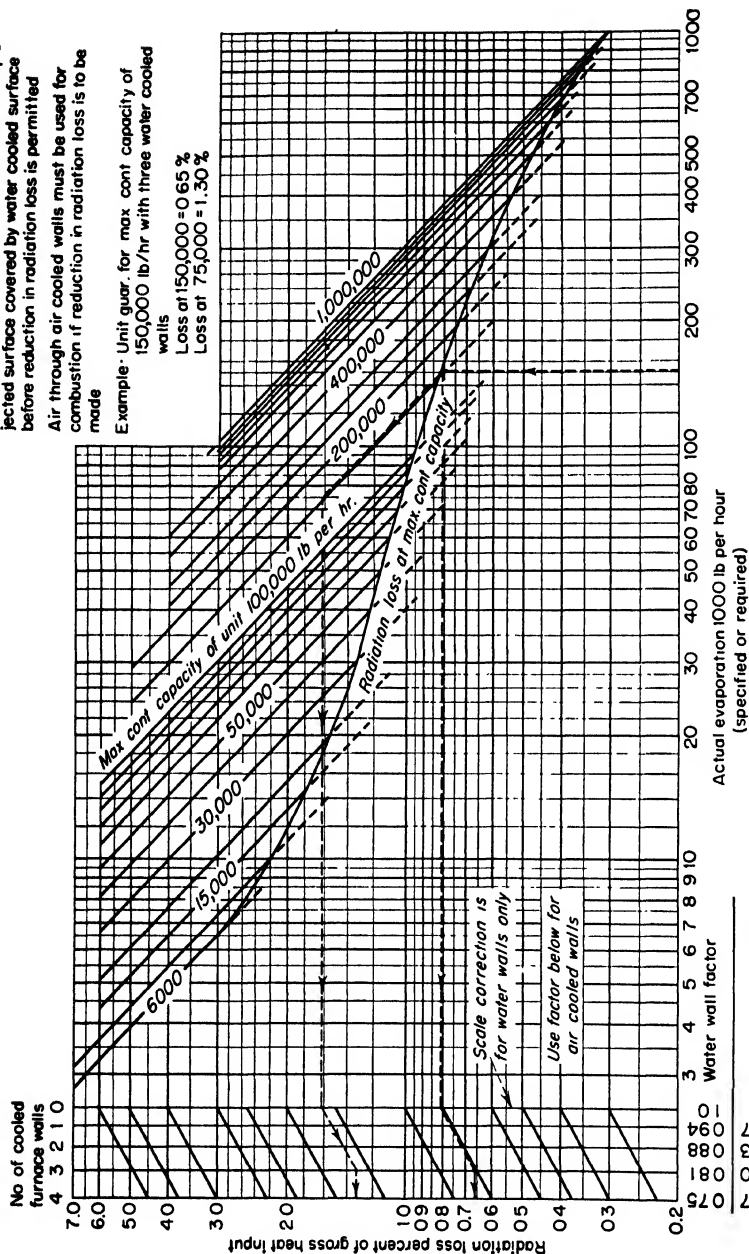


Fig. 12-24. ABMA standard radiation loss chart. To use (values taken from example at top of chart), enter at arrow at 150,000 lb/hr and move vertically to the intersection of the "Radiation Loss at Maximum Capacity" line and the "Maximum Continuous Capacity" line of 150,000 lb/hr. Move horizontally to find loss for three water-cooled walls as indicated. For the same unit at 75,000 lb/hr, from the intersection continue along the sloped "150,000 lb/hr" line to the vertical line representing 75,000 lb/hr. Move horizontally as before.

**Example of Boiler Heat-balance Calculations Using Nomographs**  
(Btu/hr basis)

Item	Data required	Method of calculation
Input	Weight of fuel fired per hr Heating value of fuel, Btu/lb	$\text{Btu/hr} = \text{lb fuel/hr} \times \text{Btu/lb}$
1. Output	Pounds of steam/hr Pressure of steam, temp of steam if superheated, or quality if saturated, for heat content of steam in Btu/lb Temp of feed water	$\text{Btu/hr} = \text{lb steam/hr} \times (\text{heat content of steam} - \text{heat content of feed water})$
2. Dry flue-gas loss	CO <sub>2</sub> % in stack, by volume Stack temp, boiler room temp, deg F Fuel heating value, Btu/lb	From Figs. 12-1 to 12-16 according to fuel, in Btu/lb $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$
3. Loss due to evaporation of water formed by hydrogen burned	Hydrogen % by weight for solid or liquid fuel Lb of water formed in flue gas/cu ft of gas burned Stack temp, and boiler room temp, deg F	From Fig. 12-17, in Btu/lb for solid or liquid fuel $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$ Water formed/cu ft of gas burned from Table 12-8 From Fig. 12-18 in Btu/cu ft $\text{Btu/hr} = \text{Btu/cu ft} \times \text{cu ft gas/hr}$
4. Loss due to evaporation of moisture in fuel	Moisture % by weight of fuel Stack and boiler room temp, deg F	From Fig. 12-19, Btu/lb $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$
5. Loss due to moisture in air	CO <sub>2</sub> % in stack Stack and boiler room temp, deg F Wet- and dry-bulb temp of intake air	From Table 11-6, lb of ideal air/10,000 Btu of fuel Lb of ideal air/lb fuel = (lb ideal air/10,000 Btu) $\times$ heating value of fuel, Btu/lb From Figs. 11-2, 11-3, or 11-4, % excess air for CO <sub>2</sub> % Lb actual air/lb fuel = lb ideal air/lb fuel $\times$ (1 + excess air %/100) From Fig. 12-20, lb of water vapor/lb air Lb water vapor/lb fuel = lb water vapor/lb air $\times$ lb actual air/lb fuel From Fig. 12-21, Btu loss $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$
6. Loss due to incomplete combustion of carbon as carbon monoxide in stack	CO %, CO <sub>2</sub> % in stack gases Carbon % by weight of fuel	From Fig. 12-22, Btu/lb loss $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$
7. Loss due to unconsumed carbon in refuse	Ash % by weight in fuel Per cent combustible in refuse	From Fig. 12-23, Btu/lb loss $\text{Btu/hr} = \text{Btu/lb loss} \times \text{lb fuel/hr}$
8. Radiation and unaccounted-for loss	For a boiler, the max rated capacity, lb steam/hr, and the number of water-cooled walls	From Fig. 12-24, the radiation loss in % $\text{Btu/hr} = \text{input, Btu/hr} \times \text{radiation loss \%}$ Unaccounted for, $\text{Btu/hr} = \text{input} - (\text{sum of items 1 to 7, inclusive} + \text{radiation loss if available})$

### METHOD 3. DIRECT CHEMICAL-MATHEMATICAL METHOD OF COMPUTING COMBUSTION RESULTS AND HEAT BALANCES

While well within the range of most field analyses and measurements, and therefore sufficiently accurate for virtually all heat-balance purposes, the calculations of the nomograph method just preceding contain some approximations. These are due to the necessary assumptions of **averages** of required air and products of combustion. The following section includes tables designed to show, in highly condensed form, methods of computing exact combustion results and heat-balance items from such data as ultimate analyses.

Tables included cover the following items:

1. Calculation of the weight of oxygen and products of combustion with zero excess air (Table 12-11).
2. Determination of the volume of the products of combustion with zero excess air (Table 12-12).
3. Calculation of CO<sub>2</sub> in the stack gases: (a) with zero excess air (Table 12-13) and, (b) with varying amounts of excess air (Table 12-14).
4. Heat-balance calculations

#### Example of Calculations.

##### Fuel analysis, West Virginia bituminous

Carbon . . . .	0.7757
Hydrogen	0.0507
Oxygen	0.0519
Nitrogen	0.0120
Sulphur	0.0270
Ash	0.0827
Total.	1.0000

Heating value = 13,850 Btu per lb, dry basis

Moisture in coal = 1.61 per cent

**Test Data.** Steam generator is operating at 45,340 lb steam per hr; its maximum rated capacity is 60,000 lb steam per hr. Steam is delivered at 125 psig, and 400°F, feed-water temperature is 181°F. Unit has four water-cooled walls.

10.34 lb steam are produced per lb coal.

Boiler room (intake air and fuel temperature) = 79°F dry-bulb  
= 71°F wet-bulb

Stack analysis: CO<sub>2</sub> = 12.8 %

CO = 0.4 %

O<sub>2</sub> = 6.1 %

N<sub>2</sub> = 80.7 %

100.0 %

Stack temperature = 500°F

Ash and refuse per cent of dry coal = 9.42 per cent

Combustible in ash and refuse = 32.3 per cent

#### Input

Btu/lb, heating value of fuel = 13,850

#### Output + Losses

1. Output,  $h_1$

$$h_1 = W_s(h_s - h_w)$$

Heat content of steam for 125 psig (139.7 psia) and 400°F = 1,221.2 Btu per lb, heat content of feed water at 181°F = 181 Btu per lb

$$W_s = 10.34 \text{ lb steam/lb coal}$$

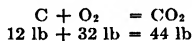
$$h_1 = 10.34(1,221.2 - 181)$$

$$h_1 = 10,770 \text{ Btu/lb coal}$$

(Continued on page 418)

**Table 12-11. Calculations of Weight of Oxygen and Products of Combustion**  
(Zero excess air per cent)

Ultimate analysis	Lb oxygen required/lb fuel <sup>a</sup>	Lb products of combustion/lb fuel
Carbon (C)	$2.666 \times C$	$\text{CO}_2 = 3.666 \times C$
Hydrogen (H <sub>2</sub> )	$8 \times \text{H}_2$	$\text{H}_2\text{O} = 9 \times \text{H}_2$
Oxygen (O <sub>2</sub> ) . . .	Decreases outside oxygen required	
Nitrogen (N <sub>2</sub> ) . .	.....	N <sub>2</sub>
Sulphur (S)	$1.000 \times S$	$\text{SO}_2 \times 2 \times S$
Ash . .		
Sum = 1.0000	Sum	Plus N <sub>2</sub> from air <sup>b</sup>
		Sum

<sup>a</sup> These constants are derived from combustion equations, e.g.,

Then

$$\begin{aligned} \text{O}_2 &= \frac{32}{44}C \quad \text{and} \quad \text{CO}_2 = \frac{44}{44}C \\ &= 2.666C \quad \quad \quad = 3.666C \end{aligned}$$

<sup>b</sup> Ratio of nitrogen/oxygen in air is 76.8/23.2; therefore outside nitrogen from air =  $76.8/23.3 \times$  sum O<sub>2</sub> required.

$$\begin{aligned} W_1 &= \text{lb dry air/lb fuel at zero excess air} \\ &= \text{nitrogen from air} + \text{sum of oxygen} \end{aligned}$$

**Table 12-12. Determination of the Volumes of Products of Combustion for Zero Excess Air at Any Stack Temperature T°F**

Lb combustion products/lb fuel from Table 12-10	Volume cu ft flue-gas constituent/ lb at standard conditions <sup>a</sup>	Volume of flue-gas constituents, corrected to stack temp T, and weights of constituents, cu ft/lb fuel <sup>b</sup>
Carbon dioxide (CO <sub>2</sub> )	8 160	$\text{CO}_2 \times 8 \ 160 \times \frac{460 + T}{460 + 32} =$
Water (H <sub>2</sub> O)	19 949	$\text{H}_2\text{O} \times 19 \ 949 \times \frac{460 + T}{460 + 32} =$
Nitrogen (N <sub>2</sub> ), from fuel and air	12 820	$\text{N}_2 \times 12 \ 820 \times \frac{460 + T}{460 + 32} =$
Sulphur dioxide (SO <sub>2</sub> )	5 611	$\text{SO}_2 \times 5.611 \times \frac{460 + T}{460 + 32} =$
		Sum of flue-gas constituents =

<sup>a</sup> One mol of any gas has a volume of approximately 359 cu ft at standard conditions of 29.92 in. Hg and 32°F. Therefore

Gas	Lb/mol of gas	Volume of gas/lb at standard conditions
CO <sub>2</sub>	44	$\frac{359}{44} = 8 \ 160$
H <sub>2</sub> O	18	$\frac{359}{18} = 19 \ 949$
N <sub>2</sub> . . .	28	$\frac{359}{28} = 12 \ 820$
SO <sub>2</sub> . . .	64	$\frac{359}{64} = 5 \ 611$
Air	28 95	$\frac{359}{28 \ 95} = 12.400$

<sup>b</sup> Volume of gas at T = volume of gas at standard conditions  $\times \frac{460 + T}{460 + 32}$ .

Table 12-13. Calculation of CO<sub>2</sub> Per Cent in Stack Gas for Zero Excess Air

$$\text{Wet basis, CO}_2 \text{ per cent} = \frac{\text{volume of CO}_2 \text{ from Table 12-12}}{\text{sum of volume of flue-gas constituents from Table 12-12}}$$

$$\text{Dry or Orsat basis, CO}_2 \text{ per cent} = \frac{\text{volume of CO}_2 \text{ from Table 12-12}}{\text{sum of volume of flue-gas constituents} - \text{volume of H}_2\text{O from Table 12-12}}$$

Table 12-14. Calculation of CO<sub>2</sub> Per Cent in Stack Gas for Varying Excess Air

Excess air per cent	Extra air, lb/lb fuel	Volume of extra air at standard conditions, cu ft/lb fuel	Volume of extra air at stack temp $T$ , cu ft/lb fuel	Volume dry flue gas, cu ft/lb fuel	CO <sub>2</sub> per cent, dry or Orsat basis
(1)	(2)	(3)	(4)	(5)	(6)
$P_{ea}$	$W_a \times \frac{P_{ea}}{100}$	$12.400^* \times (2)$	$(3) \times \frac{460 + T}{460 + 32}$	$V_g + (4)$	$\frac{V_{CO_2}}{(5)}$

where  $P_{ea}$  = excess air per cent $W_a$  = weight of air for zero excess air, lb/lb fuel, from Table 12-11

\* = volume of air/lb, from bottom of Table 12-12

 $V_g$  = sum of flue-gas constituents - volume H<sub>2</sub>O, from Table 12-12 $V_{CO_2}$  = volume of CO<sub>2</sub> taken from Table 12-12Table 12-15. Combustion Diagram: Fuel Oil<sup>1</sup>

Ultimate analysis	Weight of oxygen required, lb		Products of combustion	Weight of products of combustion, lb/lb coal	Volume of products of combustion at 600°F, cu ft/lb coal
C..... 0 8543	2 2781		CO <sub>2</sub>	3.1323	55 1
H <sub>2</sub> ... 0 1131	0 9048		H <sub>2</sub> O	1.0179	43 9
O <sub>2</sub> ... 0 0270			N <sub>2</sub>	10.5789	292 5
N <sub>2</sub> ... 0 0022			SO <sub>2</sub>	0 0068	0 82
S... 0 0034	0 0034		Total	14.7359	392 32
Total 1 0000					
From outside air					
O <sub>2</sub> to CO <sub>2</sub> ....	2 2781				
O <sub>2</sub> to H <sub>2</sub> O....	0 8778				
O <sub>2</sub> to SO <sub>2</sub> ....	0 0034				
N <sub>2</sub> in air....	10 5767				
Total.....	13 7360				

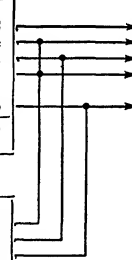
Per cent excess air	Lb air/lb fuel oil	Lb flue gas/lb fuel oil	Cu ft wet gas/lb fuel oil at 600°F	Cu ft dry gas/lb fuel oil at 600°F	Per cent CO <sub>2</sub>	
					Wet basis	Orsat, dry basis
0	13.7360	14.7359	392 32	348 42	14 0	15 8
20	16 4833	17 4833	466 02	422 12	11 81	13 05
40	19 2305	20 2305	539 72	495 82	10 2	11 1
60	21 9777	22 9777	613 42	569 52	8 98	9 67
80	24 7241	25 7429	687 12	643 22	8 02	8.55
100	27.4721	28.4721	760 82	716 92	7.24	7.7

<sup>1</sup> From GAFFERT, GUSTAF A., "Steam Power Stations," 3d ed., p. 182, McGraw-Hill Book Company, Inc., New York, 1946.

Table 12-16. Combustion Diagram: West Virginia Bituminous Coal

Ultimate analysis	Weight of oxygen required, lb		Products of combustion	Weight of products of combustion, lb/lb coal	Volume of products of combustion at 500°F, cu ft/lb coal		
C . . . . . 0 7757	2 0685	→	CO <sub>2</sub> . . . . .	2 8442	45.58		
H <sub>2</sub> . . . . . 0 0507	0.4056	→	H <sub>2</sub> O . . . . .	0.4563	17.76		
O <sub>2</sub> . . . . . 0 0519		→	N <sub>2</sub> . . . . .	8 1200	206 20		
N <sub>2</sub> . . . . . 0 0120		→	SO <sub>2</sub> . . . . .	0 0540	0.59		
S . . . . . 0 0270	0 0270	→	Total . . . . .	11 4745	270.13		
Ash . . . . . 0 0827		→					
Total... 1 0000	2 5011						
From outside air							
O <sub>2</sub> to CO <sub>2</sub> . . . . .	2 0685	→	Per cent excess air	Lb air/lb coal	Lb flue gas /lb coal	Cu ft dry gas/lb coal 500°F	Per cent CO <sub>2</sub> dry or Orsat basis
O <sub>2</sub> to H <sub>2</sub> O . . . . .	0 3537						
O <sub>2</sub> to SO <sub>2</sub> . . . . .	0 0270						
N <sub>2</sub> in air . . . . .	8 1080						
Total . . . . .	10 5572						
		0	10 5572	11 4745	252.4	18.05	
		20	12 6712	13 5885	303.5	15.01	
		40	14 7852	15 7025	354.6	12.86	
		60	16 8912	17 8085	405.4	11.24	
		80	19 0032	19 9205	456.4	9 98	
		100	21 1144	22 0317	508.6	8.96	

Table 12-17. Combustion Diagram: Natural Gas<sup>1</sup>

Per cent volumetric analysis at 62°F	Mol. wt	Weight analysis		Products of combustion	Weight analysis of products of combustion	Specific volume at 650°F	Volume products of combustion at 650°F
CO <sub>2</sub> .. 0 004	44	0 000462		0.004620	CO <sub>2</sub> .. 0.120723	18.4	2.219
CH <sub>4</sub> . . 0 921	16	0 038774		0.106628			
C <sub>2</sub> H <sub>6</sub> .. 0 041	30	0 003231		0 009475			
				0 087241			
				0.005816	H <sub>2</sub> O. 0 093057	45.0	4.187
N <sub>2</sub> . . 0 034	28	0 002506		0 555802	N <sub>2</sub> 0 555802	28 7	15 940
Total 1 000		0 044973		Total .....	0.769582		22.346

Air for combustion							
O <sub>2</sub> for CH <sub>4</sub> .. . . .	0 155096						
O <sub>2</sub> for C <sub>2</sub> H <sub>6</sub> .....	0 012062						
N <sub>2</sub> in air .....	0 553293						
Total air ..	0 720451						

Per cent excess air	Lb air/cu ft natural gas	Lb flue gas/cu ft natural gas	Cu ft flue gas/cu ft natural gas at 650°F		Per cent CO <sub>2</sub>	
			Wet	Dry	Wet basis	Orsat, dry basis
0	0 72045	0.76958	22.346	18.159	9.93	12 2
20	0.86454	0.91367	26 376	22 189	8 42	10.0
40	1.00863	1 05776	30 406	26 219	7 29	8.46
60	1 15272	1.20185	34.436	30 249	6.44	7.33.
80	1 29681	1.34594	38.466	34 279	5 77	6 47
100	1.4409	1.49003	42.496	38.309	5.22	5.79

<sup>1</sup> From GAFFERT, GUSTAF A., *op. cit.*, p. 183.

**Boiler Heat-balance Calculations, Exact Method**(Btu/lb basis)  
Procedure

Item	Data required	Method of calculation
Input	Heating value of fuel, Btu/lb	
1. Output, $h_1$ , Btu/lb fuel	Lb steam/lb fuel Pressure of steam, temp if superheated, quality if saturated, for heat content of steam Temp of feed water	$h_1 = W_s(h_s - h_w)$ $W_s$ = lb of steam produced/lb fuel fired $h_s$ = heat content, Btu/lb of exit steam $h_w$ = heat content, Btu/lb of feed water
2. Dry flue-gas loss, $h_2$ , Btu/lb fuel	Orsat stack analysis Combustion calculations for weight of gas products Temp of flue gas Temp of air	$h_2 = 0.24W_g(T_g - T_a)$ 0.24 = specific heat of gases $W_g$ = lb of dry flue gas/lb fuel $T_g$ = temp of flue gas at exit, deg F $T_a$ = temp of entering air, deg F
3. Loss due to evaporation of water formed by burning hydrogen, $h_3$ , Btu/lb fuel	Hydrogen % by weight of fuel Temp of flue gas Temp of fuel	$h_3 = 9H(1089 - T_f + 0.46T_g)$ $H$ = hydrogen % $\div 100$ $T_f$ = temp of fuel, deg F $T_g$ = temp of flue gas at exit, deg F
4. Loss due to evaporation of moisture in fuel, $h_4$ , Btu/lb fuel	Moisture % by weight of fuel Temp of flue gas, deg F Temp of fuel, deg F	$h_4 = W_{mf}(1,089 - T_f + 0.46T_g)$ $W_{mf}$ = lb moisture/lb fuel $T_f$ = temp of fuel, deg F $T_g$ = temp of flue gas at exit, deg F
5. Loss due to moisture in air, $h_5$ , Btu/lb fuel	Orsat stack analysis Temp of flue gas Wet- and dry-bulb temp of intake air, apply to Fig. 12-20	$h_5 = 0.46W_{ma}(T_g - T_a)$ 0.46 = specific heat of water vapor $T_g$ = temp of flue gas at exit, deg F $T_a$ = temp of intake air, deg F $W_{ma}$ = lb water/lb dry air $\times$ lb air supplied/lb fuel
6. Loss due to incomplete combustion of carbon as carbon monoxide in stack, $h_6$ , Btu/lb fuel	Orsat stack analysis % carbon of fuel by weight	$h_6 = \frac{CO}{CO + CO_2} C(10,190)$ CO, CO <sub>2</sub> = per cent by volume from Orsat analysis of flue gas C = lb carbon/lb fuel
7. Loss due to unaccounted-for carbon in refuse, $h_7$ , Btu/lb	% combustible by weight in refuse Ash % by weight in fuel	$h_7 = W_c(14,150)$ $W_c$ = lb unaccounted carbon in refuse/lb fuel fired
8. Radiation and unaccounted-for loss, $h_8$	For a boiler, max capacity, and No of water-cooled walls, lb steam/hr ABMA radiation chart, Fig. 12-24	$h_8 = HVF - (\text{sum of items 1 to 7, inclusive} + \text{radiation loss if available})$ $HVF$ = heating value of fuel, Btu/lb

2. Dry flue-gas loss,  $h_2$ 

$$h_2 = 0.24W_g(T_g - T_a)$$

$$\text{Excess air \%} = \frac{O_2 - \frac{1}{2}CO}{0.264N_2 - (O_2 - \frac{1}{2}CO)} \times 100$$

For a CO of 0.4 per cent and O<sub>2</sub> of 6.1 per cent, and N<sub>2</sub> = 80.7 per cent,

$$\begin{aligned} \text{Excess air \%} &= \frac{6.1 - 0.2}{0.264(80.7) - (6.1 - 0.2)} \times 100 \\ &= 38.4 \end{aligned}$$

Air for zero excess air, from Table 12-16, for the combustion calculations for this coal, is 10.5572 lb per lb coal.

$$\text{Extra air} = 10.5572 \times 0.384 = 4.060 \text{ lb air/lb coal}$$

Pounds of dry flue gas (Table 12-16), for zero excess air =  $11.4745 - 0.4563 = 11.0182$  lb gas per lb coal.

Total flue gas at 38.4 % excess air = 11.0182

$$\begin{array}{r} + 4.060 \\ \hline 15.0782 \end{array}$$

For a stack temperature of 500°F, and air temperature of 79°F,

$$\begin{aligned} h_2 &= 0.24(15.0782)(500 - 79) \\ h_2 &= 1,524 \text{ Btu/lb coal} \end{aligned}$$

3. Loss due to evaporation of water formed by burning hydrogen,  $h_3$

$$h_3 = 9H(1,089 - T_f + 0.46T_g)$$

For a hydrogen per cent of 5.07, fuel temperature of 79°F, and a stack temperature of 500°F,

$$\begin{aligned} h_3 &= 9 \frac{(5.07)}{100} (1,089 - 79 + 0.46 \times 500) \\ h_3 &= 566 \text{ Btu/lb coal} \end{aligned}$$

4. Loss due to the evaporation of the moisture in the fuel,  $h_4$

$$h_4 = W_{mf}(1,089 - T_f + 0.46T_g)$$

The 1.161 per cent of moisture becomes in terms of dry coal

$$\frac{1.61}{(100 - 1.61)} = 1.64\%$$

For a moisture per cent of 1.64, stack temperature of 500°F, and a fuel temperature of 79°F,

$$\begin{aligned} h_4 &= \frac{1.64}{100} (1,089 - 79 + 0.46 \times 500) \\ &= 20.4 \text{ Btu/lb coal} \end{aligned}$$

5. Loss due to moisture in the air,  $h_5$

$$h_5 = 0.46W_{ma}(T_g - T_a)$$

From Fig. 12-20, for a dry bulb of 79°F and a wet bulb of 71°F, the difference being 8°F, the pounds of moisture per pound of dry air = 0.014.

From item 2, the dry flue-gas loss, the air required is

$$\begin{aligned} &10.5572 \text{ lb air/lb coal for zero excess air} \\ &+ 4.060 \text{ lb extra air/lb coal} \\ &\hline &14.6172 \text{ lb air/lb coal for 38.4 % excess air} \\ W_{ma} &= 0.014(14.6172) = 0.2045 \text{ lb moisture/lb coal} \end{aligned}$$

For a moisture weight of 0.2045 lb per lb coal, a stack temperature of 500°F, and an air temperature of 79°F,

$$\begin{aligned} h_5 &= 0.46(0.2045)(500 - 79) \\ h_5 &= 39.6 \text{ Btu/lb coal} \end{aligned}$$

6. Loss due to incomplete combustion of carbon as carbon monoxide in stack,  $h_6$

$$h_6 = \frac{\text{CO}}{\text{CO} + \text{CO}_2} C(10,190)$$

For CO = 0.4 per cent, CO<sub>2</sub> = 12.8 per cent, and C = 77.57 per cent,

$$\begin{aligned} h_6 &= \frac{0.4}{0.4 + 12.8} \frac{(77.57)}{100} (10,190) \\ h_6 &= 239.2 \text{ Btu/lb coal} \end{aligned}$$

7. Loss due to unconsumed carbon in the refuse,  $h_7$

$$h_7 = W_c(14,150)$$

For ash and refuse per cent of dry coal = 9.42, and combustible in ash and refuse = 32.3 per cent,



$$h_7 = \frac{(9.42)}{100} \frac{(32.3)}{100} (14,150)$$

$$h_7 = 430.5 \text{ Btu/lb coal}$$

8. Radiation and unaccounted-for loss,  $h_8$ . From Fig. 12-24, for a boiler rated at 60,000 lb of steam per hr and operating at 45,340 lb per hr, the radiation loss is 1.09 per cent.

$$\text{Radiation loss} = 13,850 \times \frac{1.09}{100}$$

$$= 151.0 \text{ Btu/lb coal}$$

The unaccounted-for loss is found by difference (see following tabulation).

$$\text{Unaccounted-for} = 109.3 \text{ Btu/lb coal}$$

Item	Btu/lb coal	Per cent
<b>Input</b> . . . . .	13,850 0	100 0
1. <b>Output</b> . . . . .	10,770 0	77 78
<b>Losses:</b>		
2. <b>Flue gas</b> . . . . .	1,524 0	11 00
3. <b>Hydrogen</b> . . . . .	566 0	4 08
4. <b>Water-fuel</b> . . . . .	20 4	0 15
5. <b>Water-air</b> . . . . .	39 6	0 29
6. <b>CO</b> . . . . .	239 2	1 72
7. <b>Carbon-ash</b> . . . . .	430 5	3 11
8. <b>Radiation</b> . . . . .	151 0	1 09
<b>Unaccounted</b> . . . . .	109 3	0 78
<b>Total</b> . . . . .	13,850 0	100 00

## BOILER HEAT LOSSES AND THEIR CAUSES<sup>1</sup>

### Dry Flue-gas Loss

**High Pounds of Air per Pound of Coal.** This is due to high excess air revealed by low  $\text{CO}_2$ . This is the largest of all the boiler losses. The Bureau of Mines says,<sup>2</sup> "In general, the more air used in burning coal the greater is the quantity of heat carried away in the chimney gases, the loss being very near proportional to the amount of air used in combustion."

### High Flue-gas Temperature.

1. Poor transfer rates
  - a. External heating surface dirty because of soot, dust, etc.
  - b. Low  $\text{CO}_2$  resulting in excess air and in low furnace temperature
  - c. Insufficient mixing of distilled and dissociated gases and air
  - d. Incomplete combustion in furnace followed by secondary combustion in gas passes
  - e. Gases striking heating surface before combustion completed
  - f. Loss to stack of uncombined hydrogen, hydrocarbons, and CO
  - g. Stagnant gases upon any part of heating surface
  - h. Poor bathing of heating surfaces with short downward flow
  - i. Not sufficient scrubbing action and velocity of gases to wipe away gas cooled and adhering to heating surface
  - j. Short gas pass of large cross section
  - k. Short-circuiting heating surface with short downward flow
  - l. Stratification or laning of gases through open gas passes
  - m. Gas baffles leaky, broken, or fallen out of place
  - n. Rate of combustion to furnace volume too high
  - o. Poor stoker application for coal to be burned

<sup>1</sup> The Heat Balance as an Aid to Reducing Fuel Costs in Boiler Rooms, 2d ed., *Bull.* 10, The Wickes Boiler Co., Saginaw, Mich., pp. 11-15.

<sup>2</sup> *Bur. Mines, Tech. Paper* 80, p. 62.

- p. Defective leaky setting admitting excess air, cooling gases
2. Poor heat absorption
  - a. Dirty heating surfaces internally because of scale, grease, mud
  - b. Sluggish water circulation or stagnant water
  - c. Pockets of steam in gas-swept surfaces
  - d. No mud drum to hold impurities precipitated from water
  - e. Heavily overcrowding heating surface
  - f. Poor damper control
  - g. Little or no heat transferred by radiation

**Difficulty of Measuring Flue-gas Temperature Accurately.** According to the Bureau of Mines,<sup>1</sup>

Accurate measurement of the temperature of the gases as they pass through a boiler setting is extremely difficult, especially where the temperature of the gases differs greatly from that of the surrounding surfaces. Under such conditions, the results obtained by ordinary methods of measurement are seldom correct within less than 10 per cent and are frequently off 25 per cent. The errors in the measurements are due chiefly to three causes, as follows:

1. Radiation from the instruments with which the temperatures are measured. This error usually makes the observations too low.
2. Variation of the temperature of the gases at different points in a cross section of the path of the gases. This error may make the readings too high or too low, more often too low.
3. Fluctuation of temperature at any one point may cause the reading to be too low or too high.

#### Loss Due to the Evaporation of Moisture in the Fuel

1. Moisture held within the pores of the coal by capillary attraction is unavoidable.
2. Moisture appearing on the surface as mined is also unavoidable.
3. Moisture due to rain and snow during transit or storage is partly avoidable.
4. Moisture put in by fireman with hose is avoidable.
5. In the presence of moisture hydrogen usually escapes more freely (see Radiation Loss for chemical reactions).
6. Moisture is detrimental when fired in pulverized form, because of coking.
7. Moisture increases liability of spontaneous combustion.
8. Coals high in moisture are usually high in ash.
9. It may sometimes be necessary to wet coal because of its fineness, in order to hasten coking and so prevent loss due to falling through grates; or sometimes fine dry coal packs and prevents the requisite amount of air from reaching the fuel. This can be somewhat prevented by wetting. The advisability of wetting must be decided in each case, but no more wetting should be done than is absolutely necessary.

#### Loss Due to Incomplete Combustion of Carbon, as Carbon Monoxide in the Stack

1. Too thick a fire or a dirty fire
2. Too small an air supply
3. Draft not suited to thickness and quality of fire bed
4. Combustion chamber too small to permit time for mixing of gases and air
5. Furnace temperature so low that gases are not raised to igniting point
6. Fusion of ash on surface of fuel forming a blanket against air admission
7. Heavy firing at long intervals of time
8. Lack of time for combustion to be completed before reaching boiler surface
9. When fresh moist coal is thrown on a bed of white-hot coke
10. Smoke usually appearing and hydrogen and hydrocarbon gases usually lost as CO appears.
11. CO usually appearing as CO<sub>2</sub> exceeds 15 per cent

<sup>1</sup> U.S. Bur. Mines Bull. 145, p. 9.

**Loss Due to Unconsumed Carbon in the Refuse**

1. Coal unsuited to grate and furnace
2. Too large openings in the grate
3. High ash content fusing at low temperature, forming clinker
4. Too high a furnace temperature, fusing ash to a clinker
5. Too frequent cleaning of fires due to clinker. Clinker caused by
  - a. Too thick a fuel bed
  - b. Excessive slicing of fires
  - c. Thin spots in fire
  - d. Regulating draft by ashpit doors
  - e. Coal burning in ashpit
  - f. Preheating air
  - g. Much slack in coal
6. Too frequent shaking of grates
7. Too frequent dumping of grates or dump baskets of stokers
8. Too frequent poking, raking, hoeing, and slicing
9. Firing green coal onto bare spots on grate
10. Carelessness in shoveling; fuel bed not kept level
11. Too high a rate of combustion for draft available
12. Poorly proportioned grate or stoker to rate of combustion, draft, and kind of coal
13. Too small a furnace volume for rate of combustion desired
14. Loss increase as the ash content of coal increases

**Radiation and Unaccounted-for Loss**

1. Porous brick used in setting and uncovered
2. Setting not insulated, and uncovered
3. Walls too thin and large joints of mortar uncovered
4. Drumheads and shells uncovered
5. Walls heated to very high temperature
6. Hydrogen loss due to chemical reaction  $2\text{H}_2\text{O} + \text{C} = \text{CO}_2 + 4\text{H}$ , when moist coal is fired on white-hot coke
7. Carbon monoxide and hydrogen due to  $\text{C} + \text{H}_2\text{O} = \text{CO} + 2\text{H}_2$ , when water comes in contact with coke

**Table 12-18. Losses of Steam, Air, and Water Due to Leaks<sup>1</sup>**

Size of opening, in.	Daily waste of steam, air, and water, and equivalent coal					
	Steam		Compressed air <sup>a</sup>		Water	
	Lb steam wasted/day	Lb equivalent coal/day	Cu ft air wasted/day	Lb equivalent coal/day	Gal water wasted/day	Lb equivalent coal/day
$\frac{1}{16}$	573	64				
$\frac{1}{8}$	2,470	274	34,560	62	3,615	2.4
$\frac{1}{4}$	9,000	1,000	137,000	241	14,430	10.0
$\frac{3}{8}$	20,330	2,259	307,000	540	32,500	21.0
$\frac{1}{2}$	33,500	3,944	547,000	960	57,800	38.0
$\frac{3}{4}$	.. ..	..	.. ..	..	129,700	85.0
1	.. ..	..	.. ..	..	230,000	151.0
$1\frac{1}{2}$	..	..	..	..	520,000	341.0
2	..	..	..	..	925,000	606.0

<sup>1</sup> DULMAGE, W. W., Ford's Fuel Efficiency Program, A Guide for Reducing Fuel Consumption in Commercial Plants, U.S. Bur. Mines Bull. 466, pp. 154-155, 1947.

<sup>a</sup> Air computed at 90 psig.

## CHAPTER 13

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### DRAFTS AND CHIMNEYS

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## DRAFT PRODUCED BY CHIMNEYS<sup>1</sup>

The available draft in a chimney is equal to the difference in the weight of a cold column of external air and a like column of hot gas in the chimney, minus the loss due to internal friction and the loss due to accelerating the gases. The height therefore depends upon the available draft required and may be influenced by the diameter. The customary method of determining either the available draft or the chimney height (depending on which is the unknown) is to compute the theoretical draft or chimney height based on the above simple fundamental of gas column weights and then to apply a factor of efficiency to reduce this to actual draft or height.

**Maximum Theoretical Draft.** The maximum theoretical draft (MTD) which can be produced by a chimney before correcting for friction and velocity (chimney efficiency) may be expressed by the formula

$$\text{Max theoretical draft (MTD)} = 3.16HB_a \left( \frac{d_a}{T_a} - \frac{d_g}{T_g} \right)$$

where  $H$  = height of the chimney above the grates, ft

MTD = maximum theoretical draft, in. water

$d_a$  = density of the air, lb/cu ft (0.0807 under standard conditions)

$d_g$  = density of the chimney gases, lb/cu ft (depends on gas analysis. For coal will vary between about 0.0812 at 3 per cent  $\text{CO}_2$  and 0.0843 at 12 per cent  $\text{CO}_2$ . 0.084 is a good general assumption)

$T_a$  = temperature of the air, deg F *absolute* (absolute temperature equals observed temperature plus 461)

$T_g$  = mean temperature of the gases in the chimney, deg F *absolute*

$B_a$  = atmospheric pressure, in. Hg

**Simplification of Draft Formula.** Where the assumptions of 29.92, 0.08071, and 0.0840 for barometric pressure, density of the air, and density of the gases can be accepted, as with ordinary flue gases at sea level, the formula for theoretical maximum draft reduces to

$$\text{MTD} = H \left( \frac{7.64}{T_a} - \frac{7.95}{T_g} \right)$$

To simplify further the solution of maximum theoretical draft and chimney height problems, the bracketed portion of this equation, namely,  $[(7.64/T_a) - (7.95/T_g)]$ , has been worked out for atmospheric pressure at sea level and 60°F external air temperature as shown in Table 13-1.

**Table 13-1. Value of  $7.64/521 - 7.95/T_g$  for Various Chimney Temperatures**  
(Hereafter referred to as value  $J$ )

$T_g$	$J$	$T_g$	$J$	$T_g$	$J$	$T_g$	$J$
200	0 00263	300	0 00420	400	0 00541	500	0 00639
220	0 00298	320	0 00447	420	0 00563	550	0 00671
240	0 00330	340	0 00472	440	0 00584	600	0 00717
260	0 00363	360	0 00497	460	0 00603		
280	0 00394	380	0 00520	480	0 00620		

Using the value from Table 13-1, maximum theoretical draft can then be expressed as

$$\text{MTD} = HJ$$

where  $J$  is the value from the table corresponding to the chimney temperature

<sup>1</sup> "Custodis Chimneys," Alphons Custodis Chimney Construction Co., New York, 1924.

**Chimney Temperature.** The correct use of such draft formulas requires a knowledge of average chimney temperature rather than entering or breeching temperature, since  $T_g$  represents such an average. While it is true that there is a drop in temperature through a chimney, it is difficult to estimate, since the drop in temperature depends upon such factors as the dimensions of the chimney, the material of construction, and the volume of the gases. Unfortunately, data on this important point are meager. Custodis<sup>1</sup> gives the values shown as Fig. 13-1 for two chimneys. Moynihan<sup>2</sup>

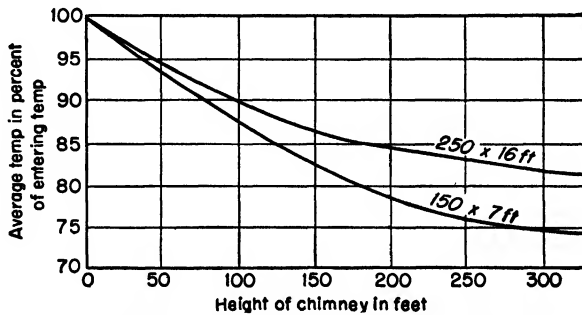


FIG. 13-1. Average temperature of gases in per cent of entering temperature vs. stack height.

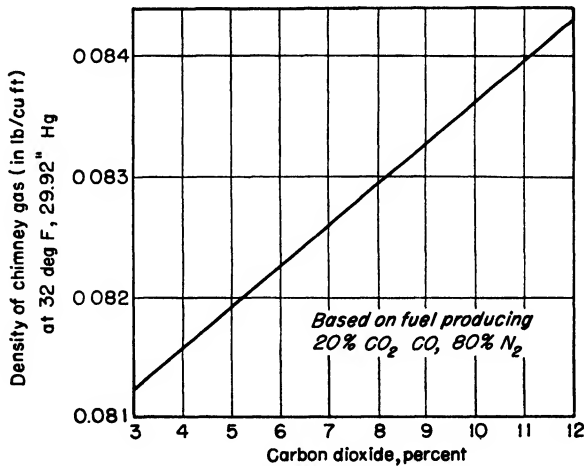


FIG. 13-2. Density of flue gases vs. per cent CO<sub>2</sub>.

finds that the mean value of  $T_g$  is usually greater than assumed. In his tests on the Cornell University chimney (225 by 11 ft), he found that the temperature drop was rather small. The assumption of too low a value of mean  $T_g$  results in a choice of chimney smaller in diameter and higher in height than conditions warrant.

While the weight of gas which will pass up a chimney increases as the temperature of the flue gases increases, a maximum is reached, according to Rankin, at about 622°F, as at any internal temperature above that the gas velocity increases less than the density of the gas decreases.

<sup>1</sup> *Op. cit.*

<sup>2</sup> MOYNIHAN, JOHN R., An Investigation of Chimney Performance, Cornell Univ., Eng. Expt. Sta. Bull. 16, Apr. 1, 1933.

**Maximum Available Draft.** The maximum theoretical draft multiplied by the efficiency of the chimney, or, in other words, minus such losses as friction and velocity, becomes the maximum available draft. This is the practical figure which should be used for chimney calculations. Formerly a common assumption of chimney efficiency was 80 per cent. The final formula for draft thus became

$$\text{MAD} = HJ \times 0.80$$

where MAD = maximum available draft to replace the maximum theoretical draft of the original formula

A similar change can be made in the other draft formulas shown, *viz.*, insertion of the efficiency fraction in the right-hand side, to change theoretical draft to available draft.

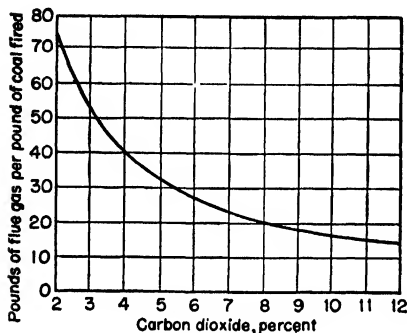


FIG. 13-3. Approximate weight of flue gas per pound of coal fired vs.  $\text{CO}_2$ .

particularly where the design is based on the maximum capacity and this maximum capacity of the plant is not approached. He also found but small air infiltration as compared with usual assumptions.

**Chimneys at Altitudes above Sea Level.** As the altitude above sea level increases, the barometric pressure decreases, or, in other words, the weight of air per cubic foot is less. There is some difference in opinion as to the correct method of calculating the height of a chimney at altitudes. However, the method commonly used of multiplying the height required at sea level by the ratio of the barometer reading at sea level to the barometer reading at altitude has given good results. Of course, if the formula used has included atmospheric pressure, and that of the altitude, rather than 29.92, has been used, such correction will not be necessary as the results will be direct for the altitude. In this section, tables calculated at sea level are so stated, while formulas not containing the barometric factor must be corrected.

The number of pounds of air required to burn a pound of any given fuel is the same, regardless of the altitude (usually about 7.6 lb per 10,000 Btu). It is therefore obvious that the volume of air furnished for combustion and the resultant volume of flue gas must increase as the barometric pressure decreases.

It is evident that, when the height of the chimney and volume of gas are increased, the friction loss is increased. In order that the same draft may be available as at sea level, it will be necessary to increase the diameter proportionately. Reliable authorities state that the diameter should vary as the two-fifths power of the ratio of the barometer reading at sea level to the barometer reading at altitude. The barometric pressure drop affects the height very much more than the diameter. Up to an

<sup>1</sup> *Op. cit.*

However, Moynihan<sup>1</sup> feels that the 80 per cent efficiency figure used is too low and that the resultant chimneys are thus higher than necessary and are capable of producing more draft than that calculated. He found that the friction loss in the Cornell tests was practically negligible, that the velocity head should probably not be charged as a loss except as a difference in velocity heads between exit and entering velocity, and that the hot gas column above the chimney top definitely tends to increase the actual draft. He concluded that the actual draft very nearly approaches the theoretical draft

**Table 13-2. Theoretical Draft Pressure in a Chimney 100 Ft High<sup>1</sup>**  
(Inches of water, assuming sea-level conditions. For any other height multiply by  $H/100$ )

Temp in chim- ney, deg F	Temp external air (barometer = 30), deg F										
	0	10	20	30	40	50	60	70	80	90	100
200	0.453	0.419	0.384	0.353	0.321	0.292	0.263	0.234	0.209	0.182	0.157
220	0.488	0.453	0.419	0.388	0.355	0.326	0.298	0.269	0.244	0.217	0.192
240	0.520	0.488	0.451	0.421	0.388	0.359	0.330	0.301	0.275	0.250	0.225
260	0.555	0.528	0.484	0.453	0.420	0.392	0.363	0.334	0.309	0.282	0.267
280	0.584	0.549	0.515	0.482	0.451	0.422	0.394	0.365	0.340	0.313	0.288
300	0.611	0.576	0.541	0.511	0.478	0.449	0.420	0.392	0.367	0.340	0.315
320	0.637	0.603	0.568	0.538	0.505	0.476	0.447	0.419	0.394	0.367	0.342
340	0.662	0.638	0.593	0.563	0.530	0.501	0.472	0.443	0.419	0.392	0.367
360	0.687	0.653	0.618	0.588	0.555	0.526	0.497	0.468	0.444	0.417	0.392
380	0.710	0.678	0.641	0.611	0.576	0.549	0.520	0.492	0.467	0.440	0.415
400	0.732	0.697	0.662	0.632	0.598	0.570	0.541	0.513	0.488	0.461	0.436
420	0.753	0.718	0.684	0.653	0.620	0.591	0.563	0.534	0.509	0.482	0.457
440	0.774	0.739	0.705	0.674	0.641	0.612	0.584	0.555	0.530	0.503	0.478
460	0.793	0.758	0.724	0.694	0.660	0.632	0.603	0.574	0.549	0.522	0.497
480	0.810	0.776	0.741	0.710	0.678	0.649	0.620	0.591	0.566	0.540	0.515
500	0.829	0.791	0.760	0.730	0.697	0.669	0.639	0.610	0.586	0.559	0.534
550	0.863	0.828	0.795	0.762	0.731	0.700	0.671	0.644	0.618	0.593	0.565
600	0.908	0.873	0.839	0.807	0.776	0.746	0.717	0.690	0.663	0.638	0.613

<sup>1</sup> "Custodis Chimneys," p. 48, Alphons Custodis Chimney Construction Co., New York, 1924.

**Table 13-3. Chimneys at Altitudes above Sea Level<sup>1</sup>**  
(Correction factors)

Altitude, ft above sea level	Barometric reading, in. Hg	R relative gas volume	R <sup>3/2</sup> ratio of chimney diameters	Altitude, ft above sea level	Barometric reading, in. Hg	R relative gas volume	R <sup>3/2</sup> ratio of chimney diameters
0	30.00	1.000	1.000	4,500	25.45	1.180	1.068
500	29.46	1.019	1.008	5,000	24.98	1.201	1.076
1,000	28.92	1.037	1.015	5,500	24.53	1.224	1.084
1,500	28.40	1.057	1.023	6,000	24.08	1.246	1.092
2,000	27.88	1.076	1.030	6,500	23.65	1.269	1.100
2,500	27.38	1.096	1.038	7,000	23.22	1.292	1.108
3,000	26.88	1.116	1.045	8,000	22.38	1.340	1.124
3,500	26.40	1.137	1.053	9,000	21.58	1.390	1.141
4,000	25.91	1.158	1.060	10,000	20.80	1.442	1.158

<sup>1</sup> "Custodis Chimneys," Alphons Custodis Chimney Construction Co., New York, 1924.

**Table 13-4. Approximate Draft Required for Various Combustion Rates<sup>1</sup>**

Fuel	Combustion rate, lb/sq ft grate/hr										
	4	6	8	10	12	14	16	18	20	22	24
Anthracite:											
No. 1 buckwheat (buckwheat) . . . . .	0.06	0.12	0.18	0.24	0.32	0.40	0.48	0.58	0.67	0.80	0.93
No. 2 buckwheat (rice) . . . . .	0.09	0.16	0.23	0.31	0.40	0.50	0.60	0.72	0.85	1.00	1.30
No. 3 buckwheat (barley) . . . . .	0.14	0.21	0.30	0.40	0.52	0.67	0.82	1.2	1.5		
Bituminous coal:											
Run-of-mine. . . . .	0.04	0.08	0.12	0.17	0.21	0.27	0.32	0.39	0.45	0.53	0.60
Pea . . . . .	0.04	0.07	0.10	0.12	0.14	0.17	0.20	0.23	0.26	0.30	0.35
Nut . . . . .	0.03	0.05	0.07	0.09	0.10	0.12	0.15	0.18	0.21	0.24	0.28

<sup>1</sup> "Fundamentals of Boiler Operation," Combustion Efficiency, Fuel Conservation Council for War.



altitude of 2,500 or 3,000 ft, though the height should be increased, no increase in diameter is needed for practical purposes.

Table 13-3 shows barometric pressure at different altitudes, the ratio of the pressures, and the value of the two-fifths power of the ratio.

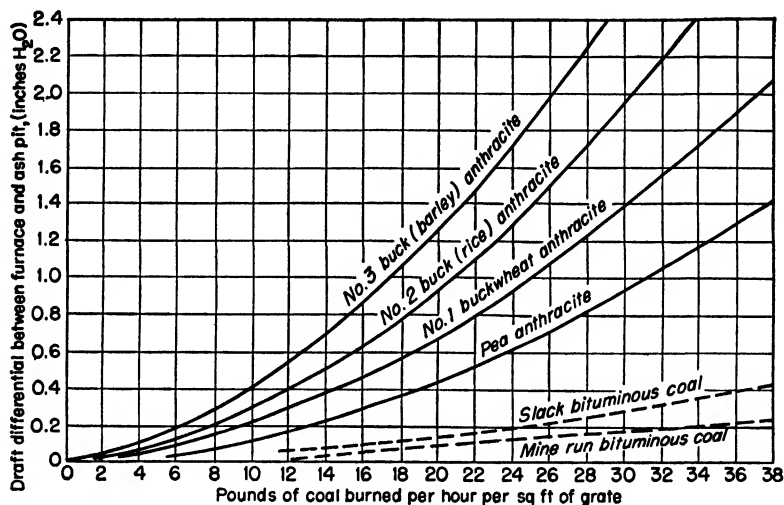


FIG. 13-4. Draft required by industrial fuel beds at different burning rates.

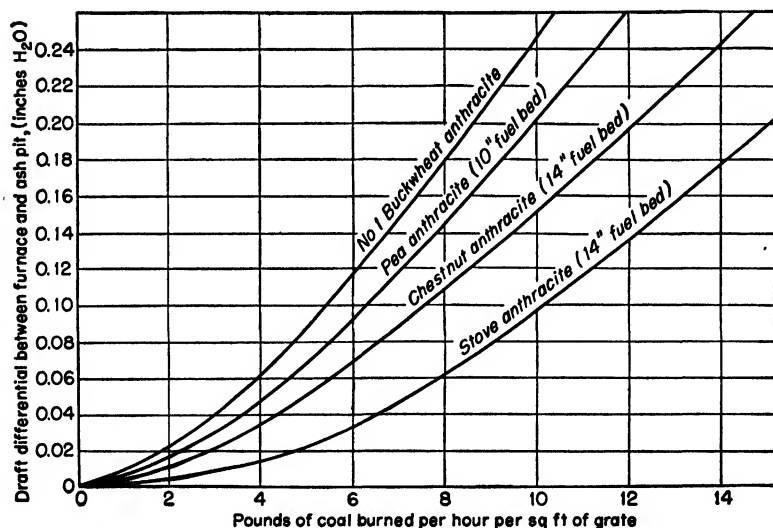


FIG. 13-5. Draft required by domestic fuel beds at different burning rates.

Where the altitudes are unusually high, the available draft required is usually reduced by changing the plant design, lowering the combustion rate, and increasing the size of the flues. If this were not done, a very large chimney would be required to give the desired results.

**Example.** To determine the size of chimney required at an elevation of 6,500 ft, assuming that a given installation requires a chimney 180 by 7 ft 6 in. at sea level and the available draft is to be the same:

Normal barometer at sea level = 30.00

Barometer at 6,500 ft = 23.65

Ratio between pressures  $R = 1.269$

Height of chimney =  $180 \times 1.269 = 228$  ft

$\frac{3}{8}$  ratio = 1.1

Diam of chimney =  $7.5 \times 1.1 = 8.25$  ft

At 2,000 ft, the chimney height would have been  $180 \times 1.076$ , or 194 ft, with practically no change in diameter necessary.

## DESIGN OF INDUSTRIAL CHIMNEYS<sup>1</sup>

The required height of a chimney above the grates is determined from the amount of required draft while the required diameter is found from the amount of gases generated in the boilers at the maximum expected load on the plant.

**Determination of Height.**<sup>1</sup> The basis for finding the required height is, as stated, the required draft, which for a natural-draft chimney is the summation of the various draft losses up to the point where the breeching enters the chimney, *viz.*, the losses through the grates and fuel bed, boiler, breeching, turns or bends, and damper friction, as well as the losses through an economizer or a sudden enlargement of an opening where these are present. This required draft is modified in the case of a forced- or induced-draft system. In the forced-draft system, the fan is assumed to take care of the loss of draft through the grates and fuel bed, and hence the required draft is less by that amount. In the induced-draft system, the fan takes care of all or part of the losses between the ashpit entrance and the fan, and hence the required draft is the least in this system for the same operating conditions.

Formulas given in the preceding section for the determination of draft are solved for chimney height when it is the unknown.

**Draft Losses through Combustion Equipment.** The draft loss in the flue or breeching depends upon its length, its cross section, the material of construction, and the number of bends. The smoother the inside of the flue, the straighter, and the nearer it approaches a circle in cross section, the less the loss at a given gas velocity. Sharp right-angle bends and sudden changes in area or shape of section are to be avoided, and all changes of direction made easily. If the chimney can be placed in the geographical center of the batteries of boilers, minimum flue lengths are usually obtained.

As a general rule, in steel flues of circular section, there will be a loss of 0.10 in. per 100 ft of length with normal gas velocities. If the flues are square or rectangular there will be an average additional loss ranging up to 25 per cent. The latter loss increases as the ratio of height to width increases. If the walls are built of masonry, there will be a further loss unless the inside is smooth.

The loss of draft through the boiler itself, *i.e.*, from the top of the fire to the point where the gases leave the boiler and enter the flues, depends on a number of factors and varies widely. Included are size and type, number of tubes and the way they are set, type of grate, method of baffling, and rating at which the boilers are operated. This loss may vary from 0.15 to 0.25 in. at rating, to 0.80 or 0.85 in. for a maximum of 250 per cent or more rating. It is advisable for the engineer to cooperate with the boiler manufacturer in determining the loss of draft to be assumed through the particular installation.

With natural-draft stokers and hand-fired furnaces, there is an additional loss through the fuel bed, dependent upon its thickness, the kind of fuel, and the type of grate. There is a certain draft over the fuel bed that will give the best results for every combustion rate and kind of fuel. With the forced-draft type of stoker the

<sup>1</sup> MOYNIHAN, JOHN R., *op. cit.* Custodis, *op. cit.*

requirement is somewhat different, for the reason that the air forced through the fuel bed by the fans relieves the chimney of this duty.

It is considered good practice to allow slight positive draft over the fire in all forced-draft installations to prevent the formation of positive pressures in the furnace. If this allowance is not made, there is the possibility of overheating the furnaces and fronts, also of objectionable gases being forced out into the boiler room.

If **economizers** are used between the boilers and chimney, there is an additional loss in draft, due to friction through the economizer. This friction loss varies within wide limits, depending upon the type of economizer, the number of tubes, the length of tubes, and the velocity of the gases passing between the tubes. The efficiency of the economizer is dependent upon the gas velocity. The economizer reduces the temperature of the flue gases, which also materially reduces the available draft, or in other words affects the required height of chimney.

Therefore, to meet heavy peak demands with economizers, the chimney should be of ample height supplemented with induced-draft fans to overcome all the previously cited losses, so that there is a constant flow of gases from ashpit to chimney. Mistakes have been made in the past by reducing the chimney height too much in such cases. This resulted in the sluggish movement of gases through the boilers and economizers with inefficient and incomplete burning of the fuel and disappointing results as to capacity.

**Determination of Chimney Diameter.**<sup>1</sup> The basis for finding the diameter is, as stated, the amount of gases generated in the boilers at maximum capacity. The volume of gas  $Q$  is equal to the area of the chimney times velocity; hence

$$Q = AV$$

where  $Q$  = volume of gas, cu ft

$A$  = area of cross section, sq ft

$V$  = velocity, fps

The weight  $W_g$  of the gases equals  $AV$  times the density of the gas,  $d_g$  or

$$W_g = AVd_g$$

$$W_g = AVd_g \frac{B_s T_s}{B_a T_g}$$

$$W_g = \frac{493}{29.92} AVd_g \frac{B_a}{T_g}$$

where  $B_a = B_g$

Since area  $A = (\pi D^2/4)$ , solving the above equation for  $D$ , we have

$$D = 0.278 \sqrt{\frac{W_g \bar{T}_g}{V d_g B_a}} \text{ ft}$$

where  $D$  = minimum internal diameter, ft

$d_g$  = density of the gas, lb/cu ft (0.0840 for flue gas may be assumed)

$B_s, B_a, B_g$  = atmospheric pressure of standard (29.92), air, and gas, respectively (in. Hg)

$T_s, T_a, T_g$  = absolute temperature (observed plus 461) at standard conditions (493°F), of air, and of gas, respectively

Hence the diameter can be determined from the weight of gases generated, which can be closely computed from the expected coal rate. The velocity must be determined or assumed (velocities as recommended by Custodis are as shown in Fig. 13-6). A change of assumption of velocity will alter the chimney dimensions. Also a known or assumed set of standard conditions for gas density and temperature and atmospheric pressure must be available as in the case of height determination.

<sup>1</sup> MOYNIEHAN, JOHN R., *op. cit.*

Some writers have advanced the method of determining an economic velocity in which the product of resulting height times diameter is the least, based on the assumption that the cost of a chimney is proportional to the volume of material. This economical velocity can be found by assuming a number of velocities and computing the resulting height and diameter; then plotting a curve of velocity vs. height times diameter and selecting the velocity giving the least product. An expression can be found for this velocity by equating the product of the equations for  $H$  and  $D$  to  $HD$ , differentiating with respect to  $V$ , the velocity, and equating the result to zero.

Inasmuch as some chimney builders are of the opinion that the cost of the stack varies more with height than with diameter, an alternate method of determining the economical velocity is suggested. This is simply to determine as the economical velocity that velocity resulting in the least product of diameter times height squared

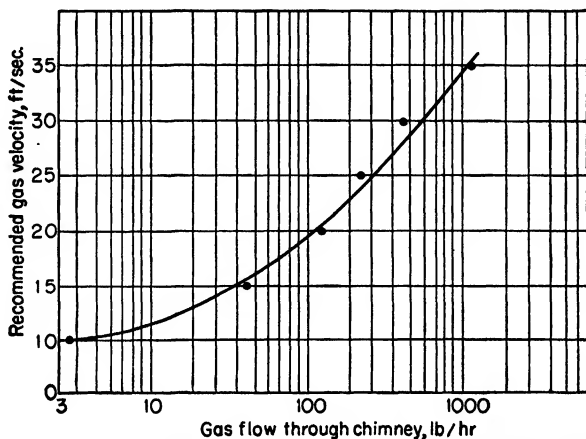


FIG. 13-6. Recommended gas velocities in chimneys. (*Custodis Chimneys.*)

( $DH^2$ ). The velocity can be found in the same manner as outlined above and would result in a chimney with a little less height and a little greater diameter.

**Gas Velocities in Chimneys.** For ordinary calculations, Custodis<sup>1</sup> recommends the chimney velocities shown in Fig. 13-6. They may be safely used for the gas quantities given without undue friction losses in the chimney or prohibitive cost of construction.

**Chimneys with Oil Firing.** While the sizes of chimneys for oil-burning boilers are determined in the same way as for coal, there are several reasons for the calculations resulting in chimneys of less height and smaller diameter. There is no fuel-bed loss; in fact, some types of burner have a forced-draft action. Some reduction in the height of the chimney is therefore permissible, but it should be borne in mind that the flue-gas temperatures may be lower, thus reducing the available draft.

The height should be sufficient to furnish the draft required at peak loads and no more. This is much more important in the burning of oil than in the burning of coal. In the latter case, there is little or no chance of too much draft. With oil, great loss in economy may result from excessive draft during periods of light load. This is especially true in plants operating with fluctuating boiler loads. Automatic control does much to reduce this evil.

In proportioning chimneys for oil-fired furnaces, consideration should always be given to the possibility of having to turn to coal for fuel because of scarcity or prices.

<sup>1</sup> *Loc. cit.*

Table 13-5. Recommended Industrial Chimney Construction<sup>1</sup>

Chimney type	Design temp, deg F	General recommendations for chimney and lining
Factory chimneys.	300-800	Lining generally not more than $\frac{1}{4}$ the height of the chimney
	600-1000	Lining need not be full length but should be increased over the customary $\frac{1}{4}$
	1000-1200	Full sectional lining of radial brick supported on corbels at intervals of about 20 ft vertically. 2-in. air space between lining and walls
	1200-1500	Independent lining for full height of radial brick. Separated throughout by 3- to 4-in. air space. Free to expand to the top. Lime, sand, and cement mortar recommended for 1500 °F and lower rather than fire clay because of stronger bond and adequacy
	1500-2000	Independent lining of <i>solid</i> radial brick for full height laid up in fire clay with small quantity of cement. Internal steel bands at every change of section. Eliminate internal ladder
	Over 2000	As above with additional lining of best refractory firebrick in lower portion inside lining but not bonded to it. Under continued temp over 2000°F firebrick lining will require periodic removal. Outside steel bands every 8 to 10 ft
Chimneys for tall buildings	Steam boiler range	Independent brick chimneys located in fireproof shafts. May be within $\frac{1}{2}$ in. of structural steel but not touching. Any shape. Or outside chimneys with plumb portion held by steel bands at 25- to 30-ft intervals. Internal partitions may be used for separation of fumes and boiler gases. Partitions not bonded
Corrosive fumes and gases	Usually the higher the temp the less the corrosion	Full independent lining with 3- to 4-in. air space. Lining of impervious, vitrified, low-lime brick laid in acid- and moisture-proof mortar and pure silica sand. Well-designed corrosion-proof cap. Protect lightning rods. Use acidproof mortar on outside top

<sup>1</sup> Alphons Custodis Chimney Construction Co.

### Chimney Design for the Handling of Gases Other Than Carbon Dioxide and Monoxide<sup>1</sup>

Chimneys and ducts are frequently called upon to perform many varied duties in addition to producing draft for steam boilers. This multiplicity of duties presents many problems. Among them are the determination of proper chimney height, size, and design where they are connected to chemical plants, dye works, smelters, paint-color factories, silvering industries with their pickling and plating departments, the picture-film industry, sintering plants, celluloid factories, and innumerable industries, all of which are confronted with the handling of some form of acid gases.

Many of these gases are destructive to ordinary brick and mortar, steel, tile, and concrete. Many are destructive at certain temperatures and harmless at other temperatures; destructive with certain conditions of moisture, but harmless with others.

The subject is an extremely diversified one requiring not only a knowledge of the mathematical and mechanical features, but a knowledge of chemistry, thermodynamics, ceramics, and subjects dealing not alone with the flow of gases, but also with the effects of different kinds of acid gases under different degrees of concentration and different conditions of moisture and temperature on a chimney.

A chimney to handle noxious gases must be designed and built not only for adequate capacity and draft, but also to resist the destructive effect of the particular acid gases, dust fumes, and temperatures. It must also be sufficiently high to provide an area of dispersion of fumes and solid particles that is sufficient to reduce the nuisance value to a tolerable minimum (see Chap. 14 for a discussion of dispersion area of various particles).

Many such chimneys are not operated in connection with steam boilers but are

<sup>1</sup> Custodis, *op. cit.*

connected directly with roasting kilns, furnaces, and other apparatus. The smoke streams omitted from such chimneys contain acids in both liquid and gaseous form. The degree of nuisance or even danger depends entirely on the degree of concentration. Plants of this nature, faced with the necessary disposition of such gases, frequently depend largely upon such primary means of separation as cyclones, scrubbers, and precipitators, all of which are fully described elsewhere. However, none is successful in removing all the objectionable elements before entering the chimney. Further, some of these separation methods tend to reduce the stack temperatures materially. Some contribute moisture to the gas stream, increase the acid mist, and sometimes add to the undesirable activity of the dust and fumes. Thus chimneys 350 to 600 ft in height, discharging the gases at high elevations where they become diffused and diluted before reaching the earth, have become common.

**Odorous Gases.** In chemical or industrial plants, where the fumes are not acid, noxious, or harmful but yet are disagreeable in their odor, the gases are easily disposed of by means of a comparatively tall chimney. As the smoke stream has no destructive content, precautions against acid action are not needed. The fumes are carried to an altitude where their diffusion in the atmosphere greatly reduces any objectionable odors.

**Fine Dusts.** The fine dust coming from roasting kilns, horizontal rotary kilns in the burning of lime, pyrites, sintering processes, etc., may also be diffused to a marked degree by emitting the dust-carrying stream at a high altitude.

Of the many gases coming from these industries, such as those of the sulphur, nitric, chlorine, fluorine, lead, and arsenic groups, the sulphur group is the most frequently encountered.

Those of the carbon group can create a smoke and cinder nuisance, but they do not tend to disintegrate a brick stack.

**Corrosive Gases.** Sulphur trioxide, sulphur dioxide, compounds of lead, and arsenious oxide are noxious and objectionable. The first of these attacks to a marked degree common brick, ordinary mortar, concrete, and steel and cannot be discharged safely through an ordinary chimney designed for use in connection with ordinary steam boilers burning coal.

Sulphur dioxide gas in the pure state will condense to a liquid at about 14°F. At any temperature above this, it remains a gas and will not combine to form a damp acid mist or liquid acid. If present in small quantities in the smoke stream at atmospheric pressure, the condensation point is much lower. Therefore, sulphur dioxide has little or no effect on a brick chimney. Precautions must be taken, however, to see that the sulphur dioxide content of the smoke stream is so diluted before it reaches the ground that it is harmless. This is accomplished by the use of tall chimneys and by means of auxiliary furnaces to raise the temperatures.

Unlike sulphur dioxide, sulphur trioxide in the presence of water vapor so common in the smoke stream of the industries mentioned, even in extremely low concentrations, will combine with the water vapor and form a fog of sulphuric acid or even liquid sulphuric acid on the walls of the chimney.

The temperature at which an acid gas will become an acid liquid depends largely upon the concentration of water vapor and acid gases in the smoke stream. The greater the concentration of sulphur trioxide and water vapor the higher the temperature at which the concentration will take place. The best practice is to maintain a temperature in the smoke stream of at least 400°F at all points.

The fumes of chlorine and nitrous oxide under certain conditions attack common brick and mortar, concrete, unvitrified tile, steel, and the common metals. The effect of these materials, particularly in the presence of moisture and low temperatures, is practically the same as the effect of sulphur trioxide. A structure to stand up

against them should follow the same general design and use of materials as one built to resist the action of sulphuric acid. Disposition of chlorine and nitrous oxide fumes by emitting them at high altitudes is common practice. If the products of combustion carrying these two gases have a low temperature, auxiliary furnaces fired at the foot of the stack can be employed to raise the temperature, add velocity to the smoke stream, decrease its density, and cause it to rise to considerable heights above the top of the chimney. The diffusion in the atmosphere is thus more completely accomplished.

**Effect of Acids on Materials of Construction.** A wet or damp acid smoke stream in contact with ordinary mortars made of cement, lime, and sand, or sand and cement, produces a swelling and puffing of both the bed and cross joints accompanied by a tremendous pressure. At times the swelling amounts to as much as 25 to 30 per cent.

A chemical change first takes place at the surface. The mortar becomes soft and of the consistency of mud. This softening and swelling finally works entirely through the walls, causing the brickwork to bulge and crack. Steel bands are useless, for the masonry will bulge between the bands and even break the bands. If, after such damage, the temperatures are raised or the chimney dries out, the inner portion of the joints may become hardened but still remain swelled. If the bricks are not hard and impervious, the exposed portions will become soft and flake off. This process continues until the entire volume of the bricks is changed into soft masses. Where the swelling of the joints is quite uniform throughout the circumference, irregular bulging of the structure may be hardly discernible. The disintegration then takes the form of vertical cracks, usually first at the top where the joints are thinnest and working downward to the base. Cracks usually increase more rapidly on the prevailing windward or weather side because of increased moisture here.

Even if acid fumes are dry, certain of them will attack ordinary mortars, turning the joint into a weak sandy mass. Bricks not vitrified and impervious share the same fate. The effect on concrete is a rapid disintegration of the whole mass.

**Acid from Fuel Oils.** Acid action has been observed from the smoke stream resulting from the burning of certain fuel oils. This is particularly in evidence where the sulphur content of the oil is high and steam-atomizing burners are used. In such installations, especially with economizers and low flue temperatures and high chimneys, special attention should be given to design.

**Chimney Design for Acid Gases.** The most important factor in handling acid gases in a chimney involves maintaining a high internal temperature. This often retards the detrimental effect on the masonry without the necessity for other expedients.

If the gases are such that temperature alone is not sufficient, it is necessary to protect the main walls perfectly by an independent lining for the full height of the structure, and with a 3- to 4-in. air space between it and the main walls. The independent lining must be built of impervious, practically vitrified, brick, very low in lime and laid up in acidproof mortar. The thinnest possible joint is imperative. The bricks should be thinly buttered or dipped and struck tightly into place. The mortar should be carefully chosen for its resistance to the particular acid involved, as well as being moistureproof.

The top of the chimney should be protected by a cap covering both the lining and main walls, and made of a material not affected by the fumes. While room should be allowed for expansion, fumes and moisture must not be allowed to penetrate under the cap.

As gases coming from the top of a chimney are often blown down the outside for distances varying from 25 to 100 ft, acid- and weatherproof mortar should be used

Table 13-6. Data Pertaining to Some of the World's Largest Chimneys<sup>1</sup>

Location..	Selby, Calif.	Anaconda, Mont.	Tacoma, Wash.	Copper Cliff, Ont.	Oroya, Peru	Colborne, Ont.	Copper Cliff, Ont.	Petsamo, Finland	Great Falls, Mont.	Hurley, N.Mex.
Owner .....	A	An	A	I	C	I	I	P	An	K
Height, ft above ground.	600	585	571	554	550	512	510	505	506	501
Diam, top inside, ft.....	13	60	25	40	42	15½	45	14½	50	20
Diam, bottom outside, ft	44	81½	49½	62	69	48½	72½	45	74	42½
Wall thickness, top, in .	7	22½	13½	8	8	6½	17	6½	18	7
Wall thickness, bottom, in	25	64	61	33	34	27	54	30	66	31½
Weight, tons.	5,200	23,700	12,700	9,000	12,000	6,000	15,600	5,200	18,500	5,100
Material.....	Concrete	Radial brick	Paving brick	Concrete	Concrete	Concrete	Radial brick	Concrete	Radial brick	Concrete
Lining .....	None	Full	Full	Full	Full	Full	Full	Full	Full	Full
Design wind pressure, lb	33	33¾	25	27½	30	27½	27½	27½	33¾	33
Draft, theoretical, in.....	0.87	2.27	2.77	2.97	1.96	1.32	2.97	3.19	2.42	1.85
Temp, avg corresponding to draft, deg F.....	150	300	350	450	350	200	450	600	350	460
Capacity, Mcf/min.....	208	3,580	630	1,580	2,080	238	2,000	361	2,480	471
Altitude, base above sea, ft	...	5,800	.....	.....	12,000	.....	.....	.....	.....	5,800
Date built .....	1937	1918	1917	1936	1936	1936	1929	1939	1908	1938

NOTE: These 10 chimneys are owned by six companies as follows: (A) American Smelting & Refining; (An) Anaconda Copper Mining; (I) International Nickel, Canada; (C) Cerro de Pasco Copper; (P) Petsamon Nikkeli; (K) Kennecott Copper.

<sup>1</sup> Alphonse Custodis Chimney Construction Co.



on the outside joints of the upper portion of the main wall. Common building lime should never be used in any part of the structure.

It is important to protect such chimneys from the entrance of moisture during shutdowns of prolonged duration; otherwise acid may be formed inside.

The use of the same chimney for fumes and gases of combustion often offers a practical solution to maintaining high temperatures and diluting the acid smoke.

### PERFORMANCE OF RESIDENTIAL CHIMNEYS<sup>1</sup>

According to Schmitt and Engdahl, reporting upon tests conducted at Battelle Memorial Institute for Bituminous Coal Research, Inc., the large number of variables involved in the operational characteristics of a residential chimney makes an accurate analytical approach to the problem of chimney design almost impossible. The paucity of dependable design data on such chimneys would seem to substantiate this statement. Schmitt and Engdahl list the most important variables as the chimney flue-inlet temperature and the rate of gas flow. These factors include the effect of velocity on friction loss and on average chimney temperature. Other variables that must be considered as being likely to affect chimney operation are height, elevation, cross-sectional area and shape, type of interior surface, conductivity of wall, leakage, outdoor temperature and humidity, specific heat and mass of chimney, tightness of house, wind velocity and direction, adjacent structures, and design of chimney top. Additional factors which must be carefully considered, even though they do not affect performance, are cost and fireproofness.

The type of fuel burned in the appliance has not been mentioned as being an important variable because the amount of flue gas emitted per Btu liberated does not vary enough between various fuels to be of significance. In practice, however, the type of fuel is of consequence relative to soot formation, because soot deposits reduce the size of the flue area and consequently increase the friction of the flue.

#### Determination of Available Draft

The available draft will be some function of the ideal draft and the losses from conduction, friction, and recirculation. Available chimney draft may be written in the following manner:

$$D_a = nD_t \quad (13-1)$$

where  $D_a$  = actual or available draft as distinguished from draft as calculated

$D_t$  = theoretical chimney draft as based on inlet temperature

$n$  = chimney efficiency

It was found by Schmitt and Engdahl that, for a small residential chimney, 10 to 25 ft in height, and with a cross-sectional area of 35 to 55 sq in., the chimney efficiency will vary only within  $\pm 10$  per cent for chimneys at the same flow and temperature conditions regardless of friction and cooling losses; therefore, the product of the theoretical draft and the efficiency obtained from a previously tested chimney, at the desired flow and temperature conditions, will give an approximate solution for the unknown available draft.

**Chimney Efficiency.** Since a rigidly complete solution for determining the chimney efficiency would be extremely unwieldy and subject to inaccuracies because of such factors as the assumption of various heat-transfer coefficients, friction factors, and other variables, Schmitt and Engdahl give us Fig. 13-7 in which efficiencies for the needed conditions of temperature and gas flow are shown as based upon such comparisons with tested chimneys.

<sup>1</sup> SCHMITT, L. B., and R. B. ENGDahl, Performance of Residential Chimneys, *Heating, Piping, Air Conditioning*, November, 1943, pp. 111-118.

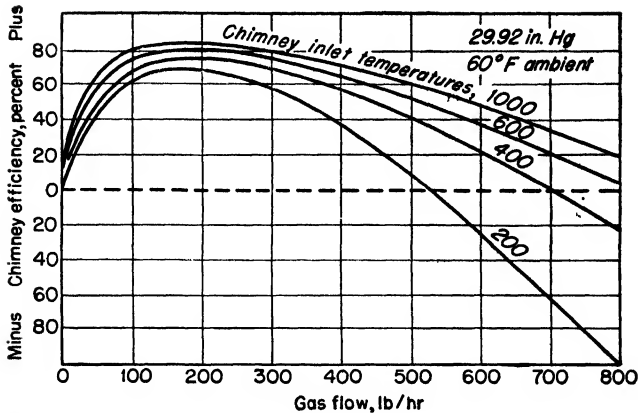


FIG. 13-7. Chimney efficiency at various temperatures and rates of gas flow.

### Theoretical Chimney Draft

The theoretical chimney draft, in inches of water, may be calculated from the following equation:

$$D_t = 0.2554 \times BH \left( \frac{1}{T_a} - \frac{1}{T_i} \right) \quad (13-2)$$

where  $D_t$  = theoretical draft

$B$  = barometric pressure, in. Hg

$H$  = chimney height, ft

$T_i$  = chimney inlet temperature, deg F absolute<sup>1</sup>

$T_a$  = ambient air temperature, deg F absolute<sup>2</sup>

**Example of Calculation of Available Draft.** Based upon Fig. 13-7 and Eqs. (13-1) and (13-2), the actual or available draft would be calculated as follows for a typical example:

Assuming chimney height of 13 ft; inlet temperature, 205°F; flow, 270 lb of gas per hr; ambient air, 60°F; and barometric pressure, 29.92 in. Hg.

The theoretical draft as calculated from Eq. (13-2), is

$$D_t = 0.2554 \times 29.92 \times 13 \left( \frac{1}{520} - \frac{1}{665} \right) \text{ or } 0.0415 \text{ in. water} \quad (13-2a)$$

From the curve in Fig. 13-7, the chimney efficiency is found to be

$$n = 0.60$$

Substituting  $D_t$  and  $n$  as determined above in Eq. (13-1), we find the available or actual draft to be

$$D_a = 0.60 \times 0.0415 \text{ or } 0.0249 \text{ in. water} \quad (13-2b)$$

In this particular example, actual test results as obtained by Schmitt and Engdahl showed an available draft of 0.0239, for an error of only 4.2 per cent.

### Determination of Gas-flow Rate

Where the per cent  $\text{CO}_2$  and the fuel rate are the only known factors, a sufficiently accurate determination of the gas-flow rate may be had from the lower part of Fig. 13-8, and the problem worked as just described.

<sup>1</sup> Fahrenheit absolute equals temperature above zero, or as read, plus 460°.

<sup>2</sup> Ambient air temperature equals difference between indoor and outdoor temperature. (Add 460° to convert to Fahrenheit absolute).

**A Graphical Calculation of Available Draft.** (Example of Use of Fig. 13-8.) Figure 13-8 is a graphical presentation of the available chimney draft over a wide range of flows for a standard 13-ft brick chimney with an 8 by 8 (nominal size) flue liner. Using performance values of a heating unit at full rating, it is possible to determine from this graph whether the chimney is adequate for the particular heating unit attached to it. By entering the chart at percentage  $\text{CO}_2$ , moving vertically to the curve representing pounds of flue gas per pound of fuel, then horizontally to the fuel rate, and vertically to the chimney inlet temperature, the available draft may be determined. The use of the chart can best be illustrated by the use of an example.

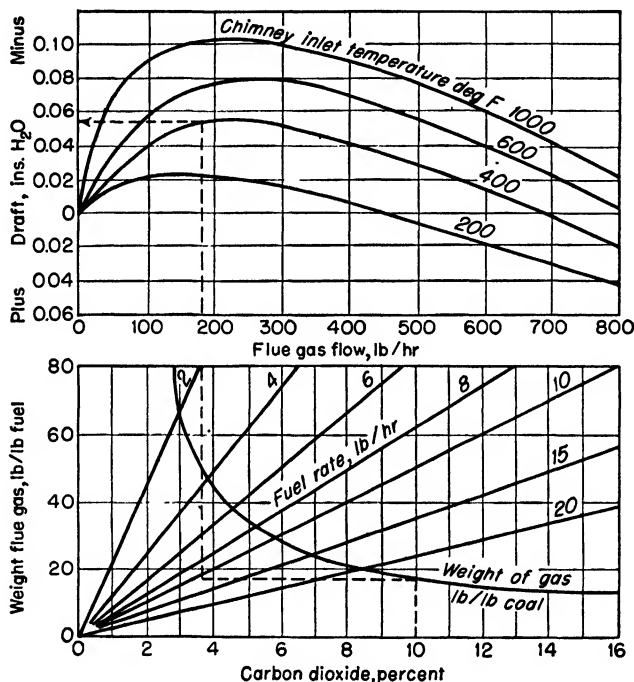


FIG. 13-8. Graphical evaluation of the available chimney draft from percentage  $\text{CO}_2$ , fuel rate, and chimney inlet temperature. [Plotted to apply to nominal 8- by 8-in. ( $6\frac{3}{4}$  by  $6\frac{3}{4}$ ) chimney, 13 ft high, burning high-volatile bituminous coal. Barometric pressure assumed 29.92. For chimneys of other heights, obtain solution from above charts and proportion to new height.]

**Example:** Given 10 per cent  $\text{CO}_2$ , fuel rate 10 lb of coal per hr, and a chimney inlet temperature of  $400^\circ\text{F}$ . It can be seen that, by plotting these values on the chart as described, there will be an available chimney draft of approximately 0.056 in. water. The margin of capacity is obtained by comparing this draft with the rated draft of the appliance.

### Variables Affecting Chimney Performance

**Chimney Construction.** Based upon tests with both tile-lined and vitreous-enameled chimneys, both insulated and uninsulated,<sup>1</sup> Schmitt and Engdahl concluded that chimney efficiency varied only slightly with the various chimneys tested and was not greatly affected by the materials or type of construction. The cross-sectional

<sup>1</sup> All chimneys tested by Schmitt and Engdahl were 13 ft high and were  $6\frac{3}{4}$  by  $6\frac{3}{4}$  (nominal 8 by 8) in. inside for the brick constructions, and 7 in. inside diameter for the vitreous-enameled chimney.

area did have some effect on the efficiency, but only insofar as it affected the friction and recirculation losses.

Chimneys other than the conventional brick type include those made of lightweight less expensive materials, such as asbestos cement, enameled steel insulated with rock wool, enameled tile, or other fireproof materials. Aside from any considerations of performance, the brick chimney does have the advantage of being recommended in the building code of the National Board of Fire Underwriters,<sup>1</sup> for oil-, gas-, or coal-fired equipment; whereas, at the present time, few of the lightweight chimneys have been approved for all three types of fuel.

Achenbach and Cole<sup>2</sup> reached similar conclusions in tests of 14 chimneys, each 15.5 ft high, and constructed of such materials as brick, shale-tile, cinder-concrete block, and enameled metal. They reported that a chimney with an enameled-steel lining surrounded by 1 in. of granular insulating material produced slightly more draft than a refractory-lined chimney of the same internal diameter at low rates of gas flow (20 cfm), but no appreciable difference was apparent at higher gas-flow rates. The chimney friction was practically the same for the 7-in.-diameter metal lining and the 7-in.-diameter refractory lining when both were clean.

**Effect of Cross-sectional Shape.** Achenbach and Cole further found that a 7-in. round flue lining is not the equivalent of a 7- by 7-in. square lining in capacity, as had heretofore been assumed. The available draft increased successively in the 7- by 7-in. square liners as the gas-flow rate was increased from 20 to 70 cfm, whereas it increased slightly in the 7-in. round liner for increasing flow from 20 to 45 cfm and decreased between 45 and 70 cfm.<sup>3</sup> The friction loss was measurably greater in the 7-in. round flue linings at a gas-flow rate of 70 cfm than in the square liners.

A 10-in.-diameter flue liner and a 7- by 11-in. rectangular liner, having equal internal areas, produced about the same available draft, had about the same loss of draft due to friction, and had equal effectiveness under comparable conditions.

**Effect of Two Adjoining Flues.** In a chimney containing two contiguous liners, one liner operating alone while the other was open at the bottom, 10 to 15 per cent less draft was produced than in a chimney containing only one liner of the same size. When both liners were in operation, receiving flue gas at the same temperature, each produced a draft nearly equal to that produced by a chimney with only one liner.

**Effect of Sealing the Bootleg.** Sealing off the air space in the base of a new well-constructed chimney at the bottom of the thimble had no important effect on the draft produced.

**Effect of Air Space in Chimney Wall.** Two chimneys were compared, identical in every respect excepting that the  $\frac{1}{2}$ -in. space between the tile lining and outer brick was grouted with cement mortar in one and was left open, or filled only with air, in the other. It was found that the presence of the air space instead of mortar surrounding the lining had no effect at all on the chimney operational characteristics. Moreover, there seemed to be no appreciable insulating value in the air space. From a mechanical standpoint, therefore, the standard grouted-liner construction is preferable, since it holds the liner in place if it becomes cracked.

**Effect of Higher Rates of Gas Flow.** When the flow of gases is increased beyond approximately 200 lb per hr, to simulate chimney operation with stoker equipment, both the draft and efficiency were found to decrease. This effect is to be expected, as the friction loss in a duct increases as the square of the rate of flow. It emphasizes the fact, however, that the comments and efficiency curves included in this section

<sup>1</sup> The National Board of Fire Underwriters, Building Code, 1943, Sec. 1101, p. 186.

<sup>2</sup> ACHENBACH, PAUL R., and SELDON D. COLE, "Masonry Chimneys," ASHVE annual meeting, Chicago, 1949.

<sup>3</sup> Gas-flow rates of 20, 45, and 70 cfm correspond to fuel-oil burning rates of  $\frac{1}{2}$ , 1, and  $1\frac{1}{2}$  gph, respectively.

should be restricted to small residential chimneys, 10 to 25 ft high, and having a cross-sectional area from 35 to 55 sq in.

**Effect of Changes in Direction or Area.** Weske<sup>1</sup> has shown that, for elbows of more than 30-deg angle of bend and of small radius ratio, separation of the gases occurs, frequently accompanied by a reversal of flow; whereas a region of eddying

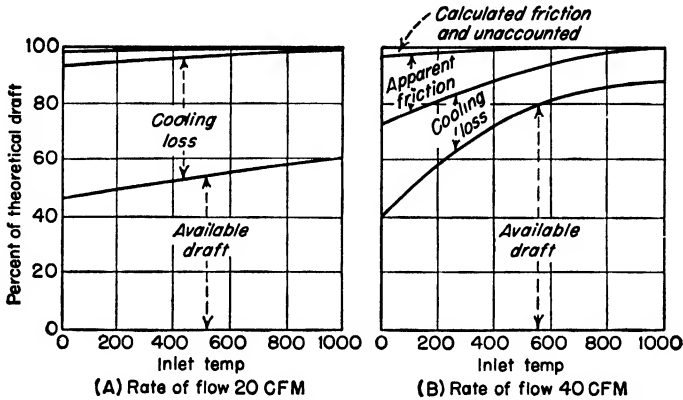


FIG. 13-9. Chimney draft balance plotted against temperature for two rates of gas flow (8 by 8, nominal, 13-ft-high chimney). [Schmitt & Engdahl.]

flow near the inside wall of curved ducts is always encountered. The chimney-temperature surveys and the work being done by Weske show that undoubtedly reversal of flow, or recirculation of gases, takes place at such points. This results in sharp reductions in the gas temperatures at these points, to introduce a discrepancy in calculations.

A common point of such occurrence is where the flue pipe enters the chimney proper. A sudden change in cross-sectional area may also be of importance. An enlargement of the horizontal flue or vertical chimney flue may result in added reversal of flow (recirculation) because of the decrease in the velocity of the gases; while a decrease in cross-sectional area would cause an increase in the frictional losses and possibly some recirculation before the restriction.

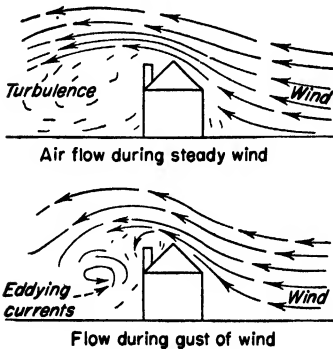


FIG. 13-10. Air flow over a building and chimney.

0.016, a value that is also recommended for chimneys in the ASHVE Guide. However, Schmitt and Engdahl found the actual measured friction losses to be much greater than the calculated theoretical, which they attribute to eddies and recirculation.

<sup>1</sup> WESKE, J. R., Experimental Investigation of Velocity Distributions Downstream of Single Duct Bends, *NACA Tech. Note 1470*.

<sup>2</sup> NIKURADSE, J., Strömungsgesetze in rauhen Röhren, *VDI Forschungsheft*, 1933, p. 361.

However, while at least some recirculation was noted throughout the entire length of the flue and chimney, particularly at low rates of flow, calculation for residential chimneys is considered virtually impossible. This thus forces the use of the empirical relationships described earlier in this section.

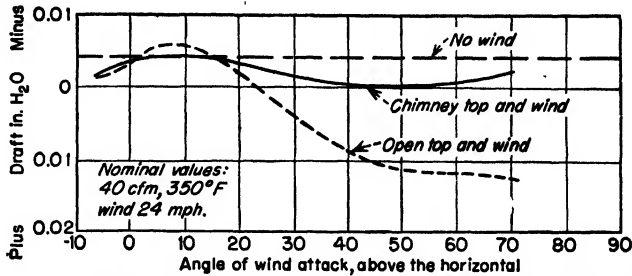


FIG. 13-11. Draft variation with change in angle of wind, with and without chimney top or ventilator.

**Wind Effect on the Chimney Top.** The varying effects of wind upon a chimney have always been a troublesome problem, inasmuch as air flowing over and around a building creates many eddies and vortexes which may affect the chimney draft to a considerable extent. These effects may be from either ram pressure upon the chimney itself or from the increase or decrease of the pressure around the house because of the changing velocity of the air stream as it flows over the dwelling. To avoid areas of turbulence, it is frequently recommended that the top of a chimney be at least 1 ft above the ridge of the house or 1 ft above the top of any nearby structures or surrounding objects. A chimney top only as high or below such wind-deflecting objects may well be in the region of turbulence, and the result may be a marked decrease in draft.

As a theoretical example of this point, a 40-mph wind hitting the top of a chimney from an angle 30 deg above the horizontal plane of the chimney top (angle of attack) will create an increase in pressure of over 0.10 in. water. As this is as compared with an available draft of some 0.09 in. water for a 15-ft chimney, it is apparent that the resultant effect upon draft would be quite serious.

**Chimney Ventilators or Caps.** As in many cases it is impractical to carry the top of a chimney above the tallest nearby structure or tree, several types of chimney caps or ventilators are offered in an effort to cancel the downdraft effect of such winds. One such ventilator, of a design as shown in Fig. 13-12, was included in the report of Schmitt and Engdahl. While they were unable to substantiate the manufacturer's claims of an actual increase in draft, they did report that a chimney ventilator, as properly installed and maintained, may be expected, in a majority of cases, to counteract the wind to a considerable extent. They caution, however, that they are not a cure for all cases, especially where the draft is poor, or where the production of soot can clog the cap.

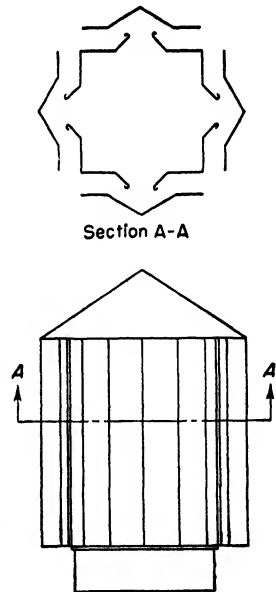


FIG. 13-12. Chimney ventilator. (Breidert Air-X-Hauster, Los Angeles.)

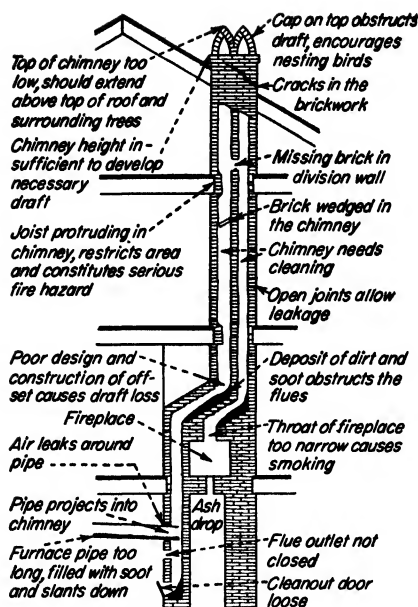


FIG. 13-13. Causes of poor draft.

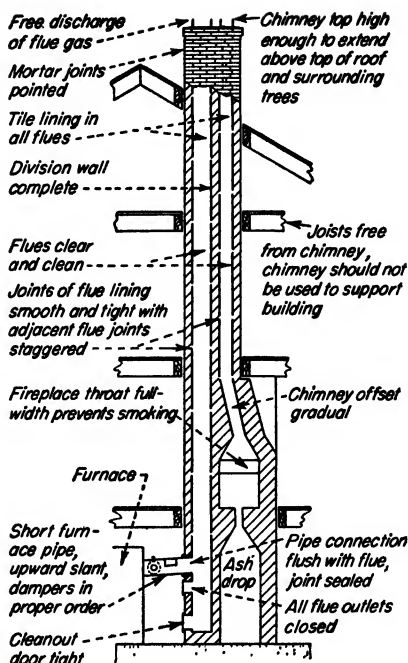


FIG. 13-14. Requirements for good draft.

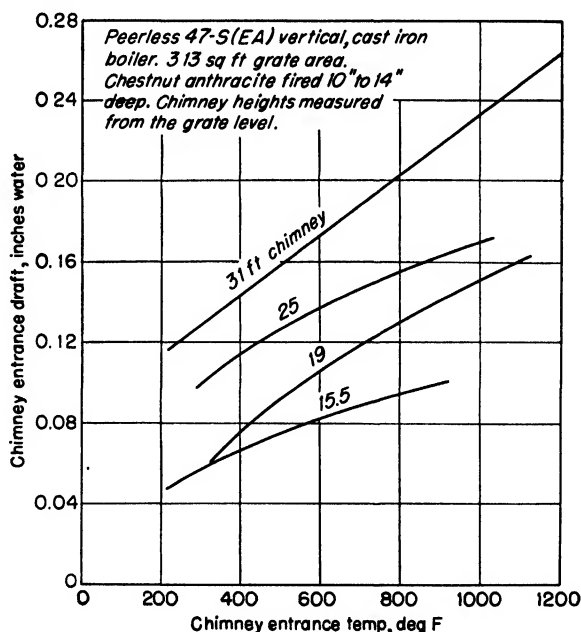


FIG. 13-15. Typical chimney entrance characteristics with an anthracite-fired boiler.

**Table 13-7. Draft Expectancy of Domestic Masonry Flues<sup>1</sup>**(Nominal 9 by 9 in. or 9 by 12 in.<sup>a</sup> Figures in body of table show probable draft in inches of water)

Temperature of inlet gas above atmospheric, deg F	Burning 1½ gal oil/hr at 8% CO₂, 67.5 cfm, or 5.06 lb/min flue gas					Burning ½ gal oil/hr at 10% CO₂, 18.4 cfm, or 1.38 lb/min flue gas				
	Stack height, ft <sup>b</sup>									
	15	20	25	30	35	15	20	25	30	35 .
200	0 056	0 079	0 098	0 112	0 118	0 044	0 068	0 080	0 080	0 060
400	0 076	0 104	0 132	0 152	0 170	0 062	0 092	0 109	0 120	0 136
600	0 086	0 120	0 154	0 180	0 202	0 071	0 104	0 128	0 144	0 164
800	0 093	0 135	0 172	0 205	0 222	0 076	0 112	0 144	0 162	0 190
1000	0 100	0 144	0 196	0 228	0 245	0 080	0 120	0 162	0 182	0 215

<sup>1</sup> Data based on tests reported in 1947 ASHVE Guide, pp. 368, 369.<sup>a</sup> Actual inside dimensions of flue linings are 7¼ by 7¼ in. and 6½ by 11 in., respectively.<sup>b</sup> Height above cellar floor. Drafts corrected to 32°F outside.**MECHANICAL DRAFT**

**Centrifugal Fans.<sup>1</sup>** Centrifugal or radial-flow fans have three fundamental blade shapes, the forward-curved, the radial (no longer used in power-plant application), and the backward-curved (Fig. 13-16). These types have variations which may be obtained by modification of the proportions or change in the curvature and angularity

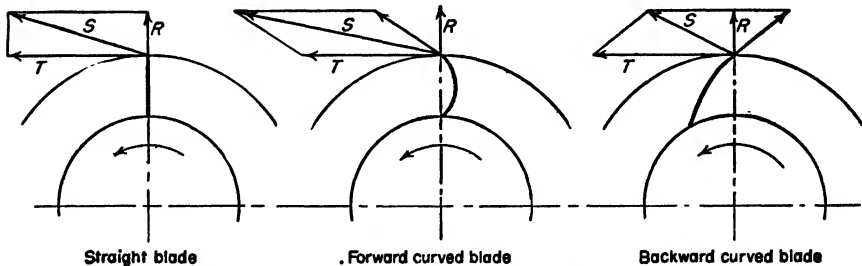


FIG. 13-16. Blade-tip velocity diagrams.

of the blades. The angularity of the blades determines the operating characteristics of a fan; a forward-curved blade is found in a fan having slow-speed operating characteristics (generally used for induced draft), while a backward-curved blade is found in a fan having high-speed operating characteristics (generally used for forced draft).

**Blade-tip-velocity Diagrams.** The blade shape and angle determine the form of the vector diagram at the tip of the blade. Shown in Fig. 13-16 are vector diagrams for the fundamental blade shapes. In this diagram,  $R$  is the radial velocity of the air from the tip of the blade,  $T$  is the blade tip speed, and  $S$  is the velocity of the air relative to the casing.

For example, the vector diagrams for the three blade types are all drawn having the same tip speed  $T$ . Since the rotors are all the same diameter, they are all rotating at the same rpm. For this condition, the velocity  $S$ , relative to the casing of the forward-curved blade, is seen to be the largest of the three types. This is due to the angularity

<sup>1</sup> ASHVE Guide, Chap 17, pp. 281-289, New York, 1935.



Table 13-8. Relative Characteristics of Centrifugal Fans<sup>1</sup>

Blade shape.....	Backward-curved	Radial	Forward-curved
First cost.....	High	Medium	Low
Efficiency .....	High	Medium	Low
Stability of operation ..	Good	Good	Poor
Space required....	Medium	Medium	Small
Tip speed .....	High	Medium	Low
Resistance to abrasion ..	Medium	Good	Poor
Ability to handle sticky materials ....	Medium	Good	Poor

<sup>1</sup> "What We Make," Catalog 500, p. 128, B. F. Sturtevant Co., Boston.Table 13-9. Fan Motor Selection Chart<sup>1</sup>

Type of motor	Hp range	Starting torque	Speed	Advantages	Disadvantages
<b>Single phase:</b>					
Resistance split phase.	Up to $1\frac{1}{4}$ hp	Medium	Constant	Low first cost	High starting current, apt to be noisy
2-value capacitor	Up to 10 hp	Good	Constant or variable	Good starting and running characteristics	High first cost
Single-value capacitor	Up to $1\frac{1}{2}$ hp	Low	Constant or variable	Good running characteristics	Not suited for belt drive
Capacitor start, induction run	Up to $1\frac{1}{2}$ hp	Good	Constant	Good starting characteristics. Low cost	Fair operating characteristics, apt to be noisy
Repulsion induction	Up to 10 hp	Good	Constant	Good starting characteristics	Fair running characteristics. Commutator, brushes, and cut-out to service
<b>Polyphase:</b>					
Squirrel cage.....	All sizes	Good	Constant	Rugged, simple construction, low cost, normal torque, normal start current or normal torque. Belt or direct	Speeds fixed by number of poles and frequency
Slip ring.....	1 hp	Good	Variable	Good starting characteristics. Speed may be varied	Higher first cost. Slip rings and brushes to service
Multispeed variable torque	All sizes	Variable	2 or 4 depending on windings	Good operating characteristics on fan load	Low torque on low speeds. Not suited to belt drive
Multispeed constant torque	All sizes	Constant	2 or 4 depending on windings	Suited to belt drive	Poor operating characteristics on fan load
<b>Direct current:</b>					
Series.....	All sizes	Good	Variable	Speed characteristics adaptable to many uses	Cannot be used on belt drives
Shunt and compound.	All sizes	Good	Constant or variable by control	Adjustable speed by field control. Variable speed by armature control. Either belt or direct	Relatively expensive and higher cost of maintenance

<sup>1</sup> B. F. Sturtevant Co, Bull. 500.

of the blade. If the three blade types all had the same casing, the forward-curved blade would deliver the greatest amount of air under these conditions.

**Characteristics Curves.** In the operation of the fan at a fixed speed, the static and total efficiencies vary with any change in the resistance which is imposed. With different designs, the peak of efficiency occurs when the fans deliver different percentages of their wide-open capacity. Variations in efficiency accompany variations in

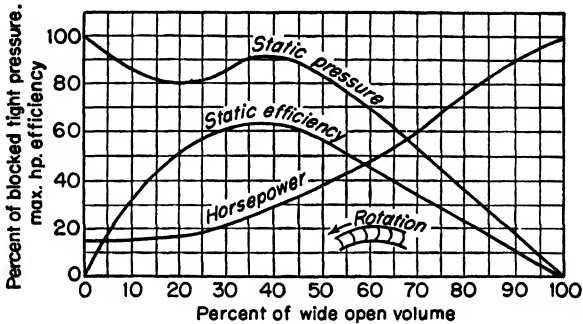


FIG. 13-17. Operating characteristics of a fan with blades curved forward. (ASHVE Guide, vol. 13, p. 286.)

pressure and power consumption which are characteristic of the individual designs and which are influenced particularly by the shape and angularity of the blades. Such variations in pressure, power, and efficiency are shown by characteristic curves in Figs. 13-17 and 13-18.

The forward-curved blade, commonly used in induced-draft application in power plants, has a low peripheral speed and a large capacity. The point of maximum efficiency for this fan occurs near the point of maximum static pressure (Fig. 13-17).

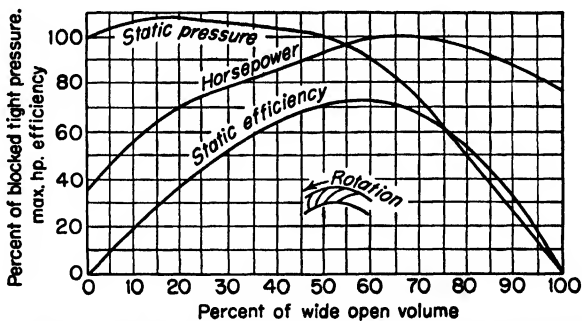


FIG. 13-18. Operating characteristics of a fan with blades curved backward. (ASHVE Guide, vol. 13, p. 287.)

Because of the shape of the pressure curve, it is possible to have two different volume outputs for the same pressure. The selection of the forward-curved-blade fan is usually based on the characteristics of the static-pressure curve to the right of the peak. Since the power curve rises continually from low to peak capacity, there is danger of overloading the motor.

The radial blade (paddle wheel) (Fig. 13-19), no longer used in power-plant work, finds application where the gases contain foreign material, fumes, and vapors. This

type of fan has a good efficiency, but the power steadily increases as the static pressure falls off, with resultant danger of motor overloading.

The **backward-curved blade**, commonly used for forced-draft application in power plants, operates at a high peripheral speed. The pressure curve (Fig. 13-18) begins to drop at very low capacity and continues to fall rapidly to full outlet opening. The steep pressure curves tend to produce constant capacity under changing pressures. Where wide fluctuations in demand occur, this type of fan is desirable to prevent overloading of motors. The maximum power requirement occurs at about maximum efficiency. Consequently, a motor selected to carry the load at this point will be of sufficient capacity to drive the fan over its full range of capacity at a given speed.

**Parallel Operation.**<sup>1</sup> Two or more fans operating on a single duct system must have suitable characteristics for such operation and be properly selected as to point of operation. Parallel operation requires that the sum of the outputs of the fans equal the duct capacity and that this equality exist for only one set of conditions.

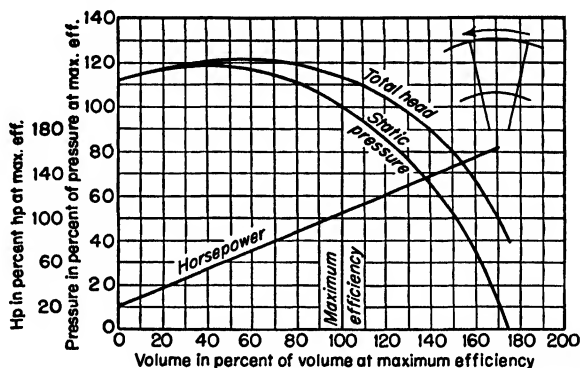


FIG. 13-19. Performance of radial-blade fan. (Cochrane Handbook, 3rd ed., p. 228.)

With proper selection, fans having the characteristic curve shape similar to the backward-curved blade are usually successfully paralleled. Successful parallel operation is possible even with the forward-curved-blade fan, but only at a sacrifice, as the region of output for this type of operation is the region of low efficiency.

When two fans are installed on one duct system, the reliability of partial load operation with one fan in the event of the failure of the other unit is usually of importance. With a self-limiting horsepower fan (see characteristic curves, Fig. 13-17 to 13-19) there is no possibility of overloading the driving motor. With other types of fans, the excess load with single-fan operation on a parallel system must always be considered in selecting motors.

**Performance of Fans.**<sup>2</sup> Fans of all types follow certain laws which are useful in determining the effect of changes of operation. These laws, applying to installations comprising any type of fan, any given piping system, and constant air density, are as follows:

*Constant Air Density.*

**Law 1.** The air capacity varies directly as the fan speed.

**Law 2.** The pressure (static, velocity, and total) varies as the square of the fan speed.

**Law 3.** The power varies as the cube of the fan speed.

<sup>1</sup> HAGEN, H. F., Centrifugal and Propeller Fans, in "Mechanical Engineers' Handbook," edited by L. S. MARKS, 4th ed., pp. 1954, 1955, McGraw-Hill Book Company, Inc., New York, 1941.

<sup>2</sup> ASHVE Guide, *loc. cit.*

**Table 13-10. Representative Capacities of Direct-drive Centrifugal Fans<sup>1</sup>**  
(With 60-cycle or d-c motors)

Speed, rpm	Mfrs. size No.	Motor hp	Wheel diam. in.	Static pressure, in. H <sub>2</sub> O at 70°F and 29.92 barometer							
				Free	1/8	1/4	3/8	1/2	5/8	3/4	1
American Blower Co. "Sirocco" Series											
1,750	0-T	1/20	4 1/2	.....	....	115					
	1-A	1/4	6	....	....	460		388	....	293	
	1 1/4-A	3/4	7 1/2	.....	....	995	....	905			
	1 1/4-A	1/2	7 1/2	....	....				.....	805	705
	1 1/2-A	1 1/2	9	..	..	1,830		1,730	....	1,620	1,470
	1 3/4-A	3	10 1/2	.	.	3,030		2,915	.	2,800	2,680
1,150	1 1/4-A	3/6	7 1/2	.	....	578	.	410			
	1 1/2-A	1/2	9	....	....	1,125		910	....	685	
	1 3/4-A	1	10 1/2	....	....	1,910		1,728			
	1 3/4-A	3/4	10 1/2	....	....				....	1,460	1,180
	2-T	1 1/2	12			2,100		1,875	....	1,760	1,650
	2-A	1 1/2	12			2,700	..	2,500	..	2,370	2,200
860	2-T	1/2	12			1,400	.	1,250	....	1,000	
	2-A	1/2	12			1,930	.	1,660	....	1,260	
	2 1/2-T	2	15			3,060					
	2 1/2-T	1 1/2	15	...		....		2,700	..	2,550	2,200
	2 1/2-A	1 1/2	15			..		3,970		3,350	2,900

American Blower Co. direct-drive "utility sets"<sup>1a</sup>

1,725	45II <sup>a</sup>	1/20	4 1/2	171	146	114					
	60H <sup>a</sup>	1/8	6	476	457	433	402	357	310	257	
	75II <sup>a</sup>	1/4	7 1/2		897	874	842	805	759	704	589
	90II <sup>a</sup>	1 1/2	9	.. ..	2,130	2,095	2,050	2,010	1,970	1,915	1,793
1,140	60M <sup>a</sup>	1/20	6	305	268	210					
	75M <sup>a</sup>	1/8	7 1/2	609	573	518	433	335			
	90M <sup>a</sup>	1 1/2	9	1,430	1,380	1,315	1,240	1,145	1,044	941	
	105M <sup>a</sup>	1	10 1/2	2,300	2,240	2,201	2,095	2,002	1,883	1,761	1,550
	122M <sup>a</sup>	2	12 1/4				3,268	3,182	3,013	2,948	2,737
860	90L <sup>a</sup>	1/4	9	1,090	1,015	905	775	609			
	105L <sup>a</sup>	1/2	10 1/2	1,730	1,648	1,536	1,396	1,266	1,086		
	122L <sup>a</sup>	3/4	12 1/4	.	..	..	2,272	2,176	1,982	1,855	1,476
2,850	30H	1/5	3	83	74	59	46				

<sup>a</sup> Ratings and model numbers shown are as for steel housings. Corresponding cast-iron housed models having capacities from 0 to 5 per cent lower are also available with the following model number changes: 60 = 1, 75 = 1 1/4, 90 = 1 1/2, 105 = 1 3/4.

## Buffalo Forge Co., direct-connected "Baby" Vent Sets

3,450	A	1/8	3 3/4	.....	192	185	178	170	162	155	140
1,750	A	1/20	3 3/4	.	85	72	47				
	B	1/20	5		217	205	185	110			
	C	1/8	6 1/4		430	410	393	370	342	270	
	D	1/6	7		602	585	566	545	520	495	275
	E	1/4	7 3/4		805	785	765	742	717	690	612
	F	1/8	9 3/4		1,130	1,080	1,030	980	920	860	705
	G	1	9 3/4	.	1,765	1,732	1,700	1,660	1,620	1,580	1,486
1,150	C	1/20	6 1/4		267	231					
	D	1/12	7		383	348	290				
	E	1/6	7 3/4		512	478	431	320	130		
	F	1/6	9 3/4		700	617	522				
	G	1/8	9 1/4		1,130	1,075	1,010	930	818	590	
860	G	1/8	9 1/4		815	720	566				

**Table 13-10. Representative Capacities of Direct-drive Centrifugal Fans<sup>1</sup>**  
(Continued)

Speed, rpm	Mfrs. size No.	Motor hp	Wheel diam., in.	Static pressure, in. H <sub>2</sub> O at 70°F and 29.92 barometer							
				Free	1/8	1/4	3/8	1/2	5/8	3/4	1
Buffalo Forge Co. "Limit Load" Vent Sets <sup>b</sup>											
1,750	2	1/2	12	...	...	1,822	1,755	1,683	1,615	1,540	1,379
	2 1/4	3/4	13 1/2	....	.	2,640	2,580	2,480	2,405	2,330	2,155
	2 1/2	1 1/2	15	....	....	3,625	3,550	3,455	3,365	3,270	3,090
	2 3/4	2	16 1/2	....	....	4,900	4,810	4,715	4,625	4,535	4,340
	3	3	18	....	...	6,400	6,300	6,200	6,100	6,000	5,780
1,150	2	1/2	12	....	...	1,077	964	828	662	417	
	2 1/4	3/4	13 1/2	....	...	1,600	1,480	1,350	1,195	1,000	
	2 1/2	1 1/2	15	...	.	2,260	2,120	1,985	1,830	1,660	1,230
	2 3/4	2	16 1/2	...	.	3,060	2,900	2,750	2,600	2,425	2,040
	3	3	18	....	....	4,040	3,900	3,720	3,550	3,380	3,000
	3 1/4	1 1/2	20	...	.	5,630	5,420	5,290	5,110	4,925	4,530
	3 3/4	3	22 1/4	....	....	7,815	7,620	7,430	7,230	7,030	6,625
	4	5	24 1/2	....	.	10,500	10,350	10,175	10,000	9,780	9,400
	4 1/2	7 1/2	27	....	...	14,220	14,020	13,820	13,620	13,420	13,020
860	2	1/2	12	....	....	665	435				
	2 1/4	3/4	13 1/2	....	....	1,050	850	542			
	2 1/2	1 1/2	15	...	.	1,530	1,325	1,075	725		
	2 3/4	2	16 1/2	...	.	2,115	1,890	1,650	1,360	1,010	
	3	3	18	...	.	2,840	2,620	2,370	2,090	1,750	747
	3 1/4	1 1/2	20	.	.	4,000	3,760	3,510	3,240	2,930	2,200
	3 3/4	1	22 1/4	.	.	5,620	5,340	5,080	4,800	4,485	3,840
	4	1 1/2	24 1/2	.	.	7,660	7,390	7,140	6,870	6,585	5,910
	4 1/2	3	27	..	..	10,400	10,100	9,870	9,560	9,270	8,540

<sup>1</sup> As compiled from manufacturers' catalogues.

<sup>b</sup> Width of single-width wheels follows: No. 2, 5 1/16; No. 2 1/4, 6 1/4; No. 2 1/2, 6 13/16; No. 2 3/4, 7 1/16; No. 3, 8 1/16; No. 3 1/4, 9 1/16; No. 3 3/4, 10 1/16; No. 4, 11 3/16; No. 4 1/2, 12 1/2.

**Example 1.** A certain fan delivers 12,000 cfm at a static pressure of 1 in. water when operating at a speed of 400 rpm and requires an input of 4 hp. If in the same installation 15,000 cfm are desired, what will be the speed, static pressure, and power?

$$\text{Speed} = 400 \times \frac{15,000}{12,000} = 500 \text{ rpm}$$

$$\text{Static pressure} = 1 \times \left(\frac{500}{400}\right)^2 = 1.56 \text{ in.}$$

$$\text{Power} = 4 \times \left(\frac{500}{400}\right)^3 = 7.81 \text{ hp}$$

**Variable Air Density.** When the density of the air varies, the following laws apply:

**Law 4.** At constant speed and capacity, the pressure and power vary directly as the density.

**Example 2.** A certain fan delivers 12,000 cfm at 70°F and normal barometric pressure (density = 0.07495 lb per cu ft) at a static pressure of 1 in. water when operating at 400 rpm, and requires 4 hp. If the air temperature is increased to 200°F (density = 0.06018 lb per cu ft and the speed of the fan remains the same, what will be the static pressure and power?

$$\text{Static pressure} = 1 \times \frac{0.06018}{0.07495} = 0.80 \text{ in.}$$

$$\text{Power} = 4 \times \frac{0.06018}{0.07495} = 3.20 \text{ hp}$$

**Variable Air Density, Constant Pressure.**

**Law 5.** At constant pressure the speed, capacity, and power vary inversely as the square root of the density.

**Example 3.** If the speed of the fan of Example 2 is increased so as to produce a static pressure of 1 in. water at the 200°F temperature, what will be the speed, capacity, and power?

$$\text{Speed} = 400 \times \sqrt{\frac{0.07495}{0.06018}} = 446 \text{ rpm}$$

$$\text{Capacity} = 12,000 \times \sqrt{\frac{0.07495}{0.06018}} = 13,392 \text{ cfm (measured at 200°F)}$$

$$\text{Power} = 4 \times \sqrt{\frac{0.07495}{0.06018}} = 4.46 \text{ hp}$$

To use - connect CFM of A to static pressure of B to locate intersection on pivot line C. Connect C to efficiency of D, to find horsepower of E.

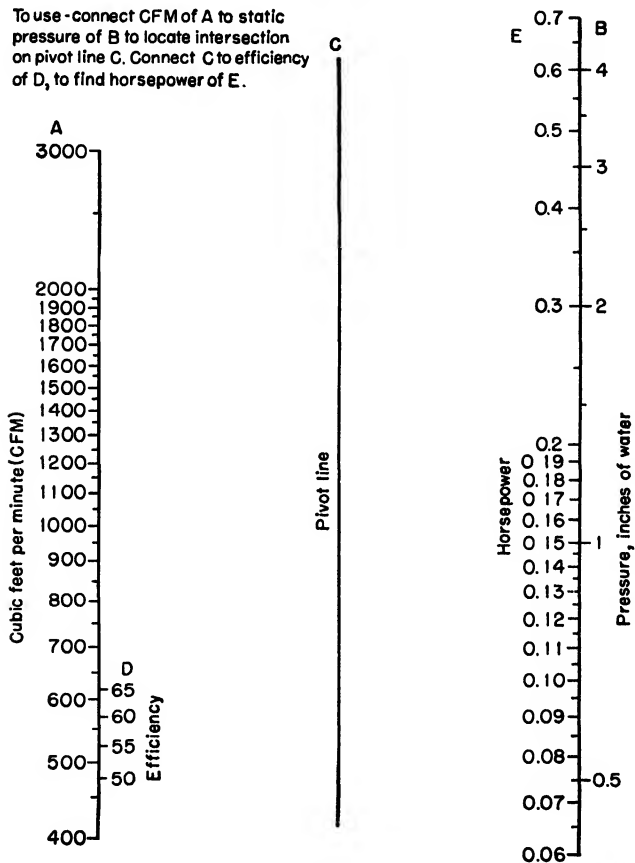


FIG. 13-20. Calculation of fan horsepower. (Small fans, 400 to 2,000 cfm.)

*Variable Air Density, Constant Weight of Air.*

**Law 6.** For a constant weight of air: (a) The speed, capacity, and pressure vary inversely as the density. (b) The horsepower varies inversely as the square of the density.

**Example 4.** If the speed of the fan of the previous examples is increased so as to deliver the same weight of air at 200°F as at 70°F, what will be the speed, capacity, static pressure, and power?

$$\text{Speed} = 400 \times \frac{0.07495}{0.06018} = 498 \text{ rpm}$$

$$\text{Capacity} = 12,000 \times \frac{0.07495}{0.06018} = 14,945 \text{ cfm (measured at } 200^{\circ}\text{F)}$$

$$\text{Static pressure} = 1 \times \frac{0.07495}{0.06018} = 1.25 \text{ in.}$$

$$\text{Power} = 4 \times \left( \frac{0.07495}{0.06018} \right)^2 = 6.20 \text{ hp}$$

**Fan Horsepower.** The horsepower required to drive a fan can be calculated from

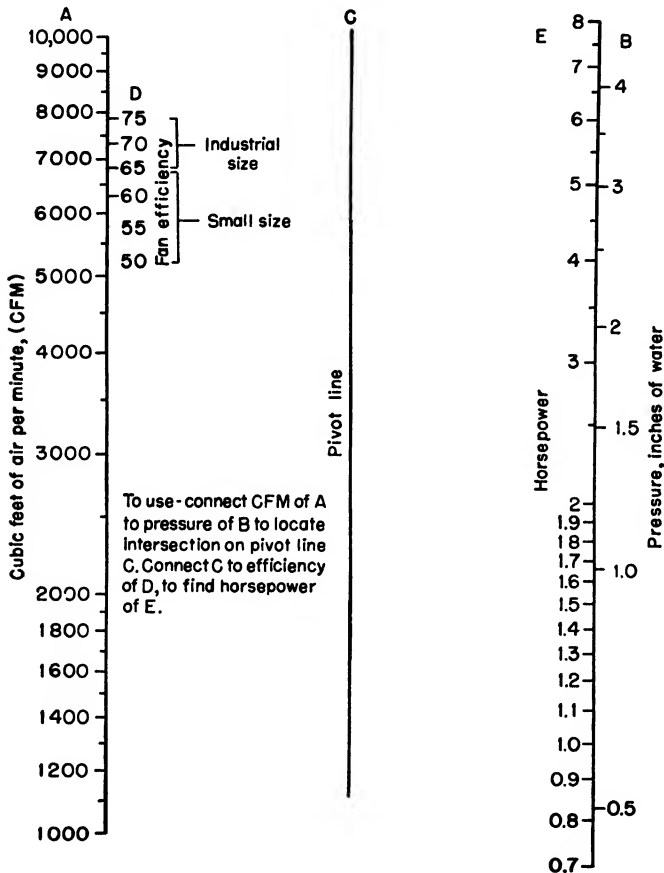


FIG. 13-21. Calculation of fan horsepower. (1,000 to 10,000 cfm.)

the following expression:

$$\text{Hp} = \frac{0.000157 \times Q \times P}{\text{fan efficiency}}$$

where  $Q$  = quantity of air flow, cfm

$P$  = pressure, in. water

A nomograph, for the solution of this expression, is given in Figs. 13-20 (small fans) and 13-21 (larger fans).

If the volume of air required for a given installation is not known, this can be secured approximately from Fig. 13-22, as cubic feet of air required at 80°F per pound of coal fired, knowing the CO<sub>2</sub> reading, the type of coal, and its heating value per pound.

Figure 13-23 is a volume-conversion chart which gives the increase of volume of gases with elevated temperatures with no pressure change.

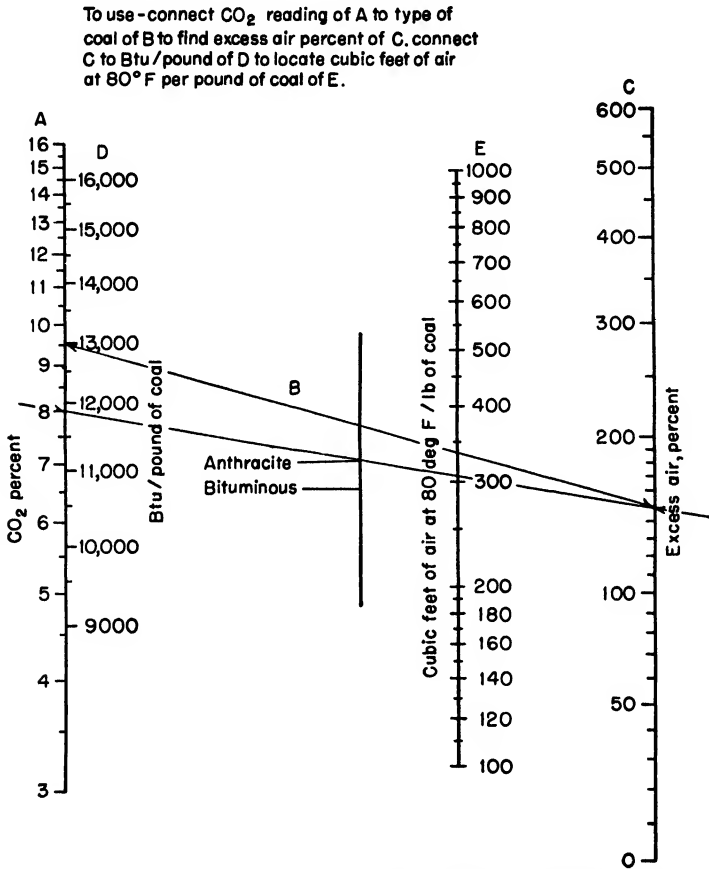


FIG. 13-22. Approximate volume of air at 80°F required for anthracite or bituminous coal for varying CO<sub>2</sub> percentages.



To use - connect Initial temp of A, to final temp of B, and locate volume multiplier of C.

Example - what is the volume of 10 cu ft of gas when heated from 120°F to 700°F ?

The volume multiplier from the chart is 2.00. Hence the volume at 700°F is  $10.0 \times 2.00 = 20.0$  cu ft.

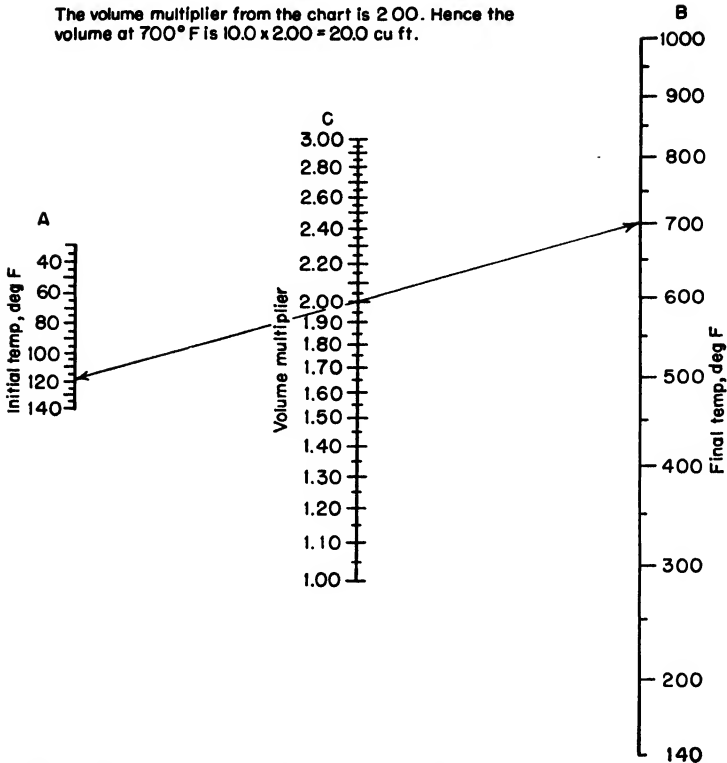


FIG. 13-23. Volume change of gases with temperature only—no change in pressure.

## CHAPTER 14

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### SMOKE, FINE PARTICLES, AND OTHER COMBUSTION REJECTS, INCLUDING SLAGS

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## THE FORMATION AND PREVENTION OF SMOKE<sup>1</sup>

All methods of burning coal constitute a two-stage process, more readily recognized when coal is burned on a grate, in which the volatile matter is expelled and burned rapidly, if at all, above the fuel bed. The remaining solid fuel is burned more slowly, usually in the form of coke (except in the case of anthracite which does not coke).

When the volatile matter in coal is not properly and intimately mixed with oxygen, the hydrocarbon molecule is "cracked" into carbon and hydrogen, the latter burning to water while the former passes through the boiler and up the stack in finely divided particles of carbon, or "smoke."

This smoke is "carbon black" and is practically noncombustible except under favorable circumstances, such as high temperature and an atmosphere rich in oxygen.

In general, the amount of smoke is proportional to the percentage of volatile matter.

The method of burning coal on a grate is better adapted to the efficient combustion of the solid portion, as it is mechanically supported for a sufficient time to effect almost complete combustion under conditions which permit the regulation of the air supply to the rate of burning and the thickness of the fuel bed. However, in surface firing (on grates), the volatile matter is released in an atmosphere deficient in oxygen, which needs to be supplemented by the introduction of air above the fuel bed. Its combustion must be effected quickly or not at all; consequently, **conditions which favor its combustion** include a furnace large enough to permit thorough mixing with air and time enough for combustion before it reaches colder parts of the boiler, provision for the introduction of air in quantities and places where it is needed, and a relatively high furnace temperature. None of these conditions except the supply of air, is necessarily a requisite for burning the solid portion of the fuel; none, except primary air, necessarily applies to **anthracite** which, by reason of its low volatile content and the absence of unsaturated hydrocarbons, does not smoke.

Many furnaces provide insufficient space and inadequate means of introducing properly distributed overfire air. Many such plants are also operating at low combustion rates with correspondingly low furnace temperatures, with the result that a considerable portion of the volatile matter escapes unburned. This causes some loss of heat, and the emission of smoke. In such plants, the percentage of volatile matter is of major importance in coal selection, the degree of importance depending upon the design and operating conditions of the plant, and the desirability of avoiding smoke.

### The Control of Smoke on Mechanically Fired Equipment<sup>2</sup>

**Underfeed Stokers.** The efficiency and smokeless operation of underfeed stokers depends on close adjustment of the rate of fuel and air feed. With these, properly proportioned combustion should be highly efficient and practically smokeless, provided only that the conditions of design, such as furnace volume, are correct.

When underfeed stokers offend from the smoke standpoint, it is usually due to conditions brought about by the start-and-stop method of operation; in such cases, smoke will be greatly reduced by adjusting the stoker so that its operation will be as nearly constant as possible.

Dense smoke is given off during the period when the fuel bed is being worked or broken up; also when the stoker is stopped as by a pressure switch. In the latter case, smoke is due to the fact that, when the stoker fan stops, distillation of gases continues with insufficient air for their combustion.

Since all the air requirements are supplied by the forced- (and induced-) draft fans,

<sup>1</sup> GOULD, G. B., "Symposium on Significance of Tests of Coal," ASTM, Vol. 37, Part II, p. 352, 1937.

<sup>2</sup> "Smoke," Perfex Corp., Milwaukee, 1947.

the chimney is primarily a means for carrying off the products of combustion. It should thus be controlled to prevent excess draft either by a barometric damper maintaining constant draft or by an automatic system to regulate the uptake damper so as to maintain constant furnace pressure regardless of the fuel and air feed. This is important in smoke, since it has been established that overfire drafts of  $\frac{1}{10}$  in. or less are unlikely to carry ash particles out of the furnace.

#### *Smoke-prevention Suggestions.<sup>1</sup>*

1. Furnace volume should be ample for conservative heat release; setting height must be related to flame travel.

2. Stoker area should be adequate to carry maximum load at a reasonable burning rate (depends on stoker type, whether or not furnace is water-cooled, etc.).

3. Water cooling in furnace or in stoker itself may reduce clinkering difficulties and hence extend range of coals.

4. Avoid overloads and attendant high burning rates. A change to a higher quality coal may reduce effect of overload.

5. Keep fire out of retorts. If burning in retorts occurs, look for too thin a fuel bed, an empty hopper, or improper banking.

6. Make sure fuel feeds uniformly over the grate. Change position of secondary rams or pushers until uniformity is obtained.

7. See that grate bar ends are always covered. Do not remove ash or clinker that stays on grate bars after dumping. Let normal stoker operation bring it down.

8. Learn proper fuel-bed thickness for your particular coal. It runs about 5 to 7 in. for single retorts, 14 to 18 for multiple.

9. If fuel bed is too heavy, fire becomes uneven, air distribution falls down, holes develop, smoke forms. Too light a fuel bed may produce retort troubles.

10. Do not work the fire more than is needed. Even the fuel bed out by lightly raking the surface. Forget the slice bar.

11. Hold overfire draft to about 0.1 in. A rule of thumb for underfire draft calls for 0.1 in. for each 10 lb of coal burned per sq ft per hr.

12. Always keep a flow of air through grates except when on bank.

13. Maintain a clean fire and clean ashpit.

#### *Coal Selection.*

1. Single-retort underfeeds handle most bituminous coals and anthracite. Preferred choice limits top size to from  $\frac{3}{4}$  to 2 in.

2. Usual specifications call for 2-in. nut-and-slack with no more than 50 per cent through a  $\frac{1}{4}$ -in. round-hole screen.

3. Multiple-retort units handle a range of bituminous coals. Top size runs about 2 in. Best results are usually had with caking coals having a relatively high ash-fusion temperature.

4. Caking qualities of coal should be suited to amount of agitation stoker gives.

<sup>1</sup>Power, May, 1948, pp. 84-87.

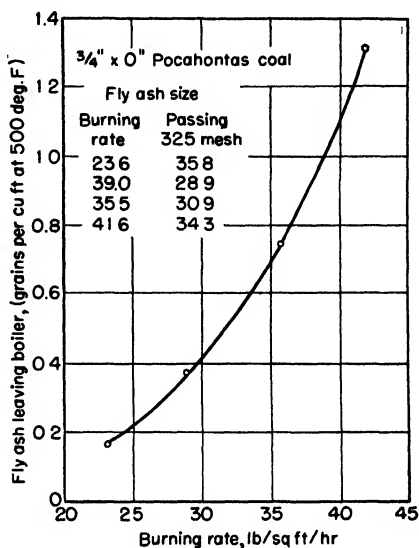


FIG. 14-1. Fly-ash carry-over from multiple-retort stoker. (Miller, Carl T., "What Can the Small Plant do About Fly Ash," Bituminous Coal Research, Inc., 1949.)

**Traveling Grates.<sup>1</sup> Smoke-prevention Suggestions.**

1. Furnace must provide positive mixing of rich and lean gas coming off fuel bed by either arches or overfire jets or both.
2. Older arch furnaces may have inadequate volume and be sensitive to fuel change.
3. Positive means for controlling air flow to various grate zones must be provided in stoker design and maintained in good working order.

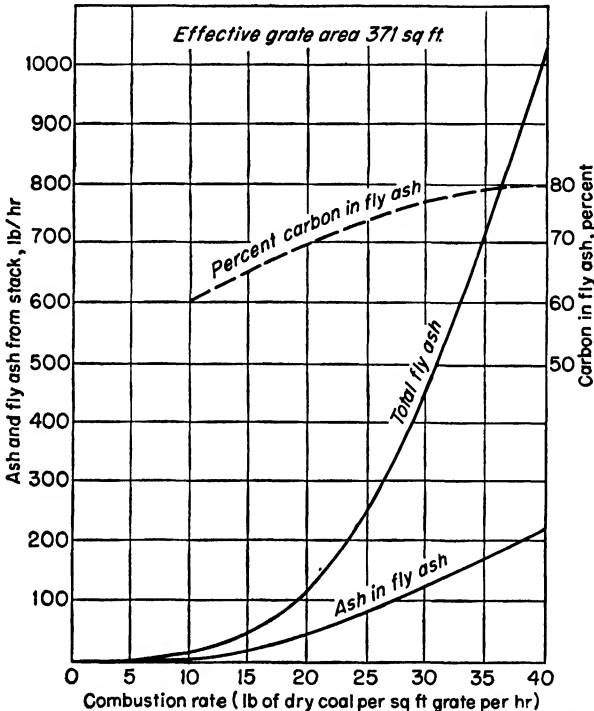


FIG. 14-2. Fly ash discharged to atmosphere from anthracite-burning traveling-grate stoker. (Gladden, C. S., "Cinder and Fly Ash Factors when Burning Small Anthracite on Traveling Grate Stokers," ASME, *Fuels Conference Paper*, p. 7, 1946.)

4. Maintain an even fuel bed. Rate of ignition controls grate speed and fuel-bed thickness.
5. Air flow directly affects ignition. Be constantly on guard against air leaks into the furnace. Such leaks break down pressure difference across fuel bed, lower the ignition rate.
6. Natural-draft grates have about 20 per cent air space. Below 0.1-in. draft, overheating of grates may be encountered. Too high a draft (over 0.5 in.) causes excessive gas velocities, cinder carry-over. Usual range is 0.1 to 0.15 in.
7. Forced-draft units have 7 to 10 per cent air space in the grate. Draft loss across the fuel bed runs about 1.5 to 2.0 in.
8. Stoker design provides for regulating air flow to different zones of the grate. For best results, air distribution must be adjusted carefully and maintained at correct flows.

<sup>1</sup> *Ibid.*, pp. 88-91.

9. Keep ashpit and undergrate areas free from siftings. Neglect can cause warping of grate surfaces and wind-box sections, with consequent loss of control of the air flow.

10. Make sure mixing is thorough. If not adequate, install overfire air jets.

#### *Coal Selection.*

1. These units work best on free-burning coals, prove suited for anthracite and coke breeze.

2. Ash content should be above about 6 per cent to ensure protection of rear grate section.

3. With natural draft (0.1 to 0.15 in.), coal having a top size of  $1\frac{1}{4}$  in. gives good results. Heavier draft permits coals of  $1\frac{1}{2}$ -in. top size having range of size normally occurring in crushing.

4. When burning anthracite, No. 3 buckwheat (barley) and No. 4 buckwheat are preferred sizes, the latter where special grates have been provided, and usually on the larger stokers.

5. Forced-draft grates can handle higher percentages of fines, smaller top size.

**Spreader Stokers.**<sup>1</sup> The spreader stoker when properly adjusted and supplied with adequate overfire air is not usually a smoke offender, but it will be a serious offender from a fly-ash standpoint if adequate precautions are not taken. Since a considerable portion of the fuel bed is burned in suspension, the resulting ash particles are very light and are easily carried over the bridge wall and out the stack. In view of this fact, overfire draft must be carried at a very low value, and control must be efficient and precise.

With the majority of underfeed stokers, overfire drafts up to  $\frac{1}{10}$  in. are generally permissible, but in the case of spreader stokers this draft value must usually be carried lower. Very low drafts are usually considered injurious to boiler settings, but this must be provided for in the operation of spreader stokers by furnishing adequate refractories. The customarily low air pressures carried in the plenum chamber do not tend to blow fly ash off the fuel bed, but the lightness of the particles burning in suspension must be considered and provided for in determining the draft adjustment for a coal of given fineness consist.

Because so much of the volatile matter in the coal is released and burned in suspension, overfire air is essential with spreader stokers. The capacity and placement of the jets is dictated by the fuel to be used.

On all but the most unusual circumstances, methods for the recovery of fly ash, usually with a return to the furnace for subsequent burning, are also essential.

#### *Smoke-prevention Suggestions.*<sup>1</sup>

1. Provide ample furnace volume and setting height to ensure smoke-free operation.

2. Turbulence is essential to good mixing over the fuel bed; install overfire if needed to avoid stratification.

3. Cinder collection and reinjection are often desirable to reduce dust emission and to keep down carbon loss to the stack.

4. Automatic control pays dividends.

5. Too high a percentage of fines may put too much of coal in suspension for furnace volume and available combustion time, cause excessive dust emission.

6. Keep a thin, level fuel bed; a heavy one clinkers and smokes.

7. Both under- and overfire draft should be held relatively low, at values consistent with a slight negative furnace pressure.

8. Low wind-box pressure, with relatively high grate resistance, avoids heavy fluctuations as fuel-bed thickness changes, also heavy cinder carry-over, and in

<sup>1</sup> *Ibid.*

extreme cases, blowholes. Holding overfire draft low avoids high gas velocities. It is a good idea to restrict fuel feed to about a minute's supply.

9. Remember that rate of ignition drops on low-load operation and that smoking can develop as a result.

10. Clean fire pits and ashpits at regular intervals. Siftings in ashpits, once ignited, can damage grates, cause loss of air control.

11. Set up the correct banking procedure and follow it.

12. Check the damper position, baffle condition, and furnace walls periodically.

#### *Coal Selection.*

1. Spreaders do best on coals under about  $1\frac{1}{4}$  in. with preferred size of about  $\frac{3}{4}$  by 0 in. nut and slack. Coarse coals tends to wear the feeders and may cause clinker.

2. Watch size consist of coal; lack of uniformity should be avoided.

3. Avoid segregation by maintaining hopper half full at all times and by using nonsegregating chutes, mechanically operated spouts, or traveling larries.

4. Spreaders handle a wide range of coals from lignite through the various types of bituminous coal, but not 100 per cent anthracite.

**Pulverized Coal.** *Emissions from Pulverized-coal Plants.* When coal is burned in pulverized form, in suspension, the volatile matter is released more rapidly in an atmosphere still rich in oxygen, mixes with it quickly by diffusion, and the furnace temperature is higher than is normally found in hand-fired or stoker-fired furnaces. This combination of conditions is very well adapted to the combustion of the volatile matter.

In a pulverized-coal furnace, the finely divided particles of solid coal must be permitted sufficient time to burn and must be kept in contact with a steady renewing supply of air in the presence of a high temperature, or they will escape unburned. The heat rapidly released in the combustion of the volatile matter aids in the ignition of the solid, or fixed carbon.

*Classification of Pulverized-coal Plant Emissions.* Pulverized-coal plants do not ordinarily produce true smoke but rather a dust consisting of particles which, though they appear very small to the eye, are actually very much larger in size than those produced by the volatile matter.

When the particles from a pulverized-coal stack are coarse and, on account of their size, fall freely under gravity, the condition is called a "dust." If the particles are small enough to fall slowly at a constant velocity, it is known as a "cloud." When, however, the particles are so extremely small that they show no signs of settling, but are driven about by the bombardment of the gas molecules, a condition exists called a "smoke."

#### *Smoke-prevention Suggestions.*<sup>1</sup>

1. Be sure pulverizer capacity is adequate to deliver fuel of desired fineness at all loads with usual moisture content.

2. Furnace must provide for full flame travel and have proper balance between uncooled and cooled surface to ensure good ignition.

3. High degree of turbulence is necessary for controlling "tail" of combustion.

4. As far as possible, operate pulverizers near best capacity level.

5. Maintain air preheat at proper level, usually in the neighborhood of 500°F.

6. Take periodic samples of mill output to keep to desired fineness.

7. Check pulverizers regularly for wear; make required adjustments to maintain desired fineness.

8. Put in orifices or directional vanes if feed distribution is not uniform.

9. Vibrators in raw-coal feed to pulverizer keep wet coal moving, avoid "hang-ups."

<sup>1</sup> *Power*, January, 1948, pp. 76-79.

10. Check all damper and vane settings in air-supply lines periodically.
11. Hold primary air as close as possible to best ignition-air ratio for all loads.
12. Be sure burners are adjusted to provide right flame shape, air distribution, and ignition point within the furnace.
13. Watch percentage of excess air in relation to ash content of fuel. As ash content increases, percentage of excess air must be increased to hold combustible loss at a fixed level. Eventually it becomes a question of balancing loss in combustible (most of which goes up stack) against dry-gas loss.
14. Make sure that dust collectors operate at design conditions to do an effective job.

#### *Coal Selection.*

1. Small mills do best on coals up to about  $\frac{3}{4}$ -in. top size. For medium and large mills, best top size runs about 1 to  $1\frac{1}{2}$  in., respectively. For any specific mill, maker's specifications should govern.

2. Fineness of pulverization depends on grindability, ash content, moisture, etc. These may also affect mill capacity. In selecting coals, bear these factors in mind, remembering also that desired fineness is influenced by such factors as volatile content.

**Oil Burners.** Smoke in oil-burning installations is caused by several related factors. In the order of their most frequent occurrence, they are:

1. Too much oil being fed into a cold furnace on starting, and the consequent failure or partial failure of combustion.
2. Insufficient air (indicated by a smoky flame), usually as a result of too small an air port, or lack of draft.
3. Excessive furnace draft, which, in combination with incomplete combustion, acts to draw the unburned gases (smudge) through the boiler passages and up the stack.
4. Faulty atomization, due to insufficient preheat (indicated by sparks in the flame) or failure to secure sufficient temperature of oil before starting. Also caused by burner-tip condition, by pulsation (pressure difficulty), and by feed-line clogging.
5. Insufficient draft loss through the boiler (in water-tube boilers) due to faulty baffle conditions.

Constant emission of smoke from an oil-burning installation is inexcusable. The factors to be considered are, in the proper sequence, burner condition, preheat, air and oil mixture, boiler condition, and control of draft.

Domestic and small commercial oil burners are usually equipped with forced draft or mechanical means of air supply, and their adjustment is thus a one-time matter of properly balancing the fuel and air supply for maximum efficiency without smoke.

In larger commercial and industrial oil burners, operation is usually by natural draft. The oil burner atomizes the oil and furnishes a certain proportion of the total air requirements as primary air intermixed with the oil; the balance of the air is introduced into the furnace by natural draft introduced through secondary ports, usually located below the burners on the boiler front. Depending on their design and the method of operation, such burners furnish from 5 to 15 or even 25 per cent of the total air requirements as primary air.

It is important that the secondary air entering the furnace be introduced in such a manner that it mixes intimately with the flame of the burner and that it does not escape around the flame to create cold-air strata. Secondary ports are of many types and vary widely in their area and their air-admission capacities and characteristics. Most air ports are of checkerwork brick, in which the efficiency of the open orifices is about 80 per cent. Thin plate openings in steel boiler fronts have an efficiency factor of about 65 per cent, while a characterized mouthpiece may have an efficiency of 95 to 98 per cent. With such figures at hand, Table 14-1 can be used to calculate the resultant air quantities to be anticipated.



If the air ports are insufficient in area for operation at low draft, and if their construction and design is improper, it is of vital importance that they be rebuilt if efficient and smokeless operation is to be accomplished.

In summation, smokeless operation results from the combination of adequate pre-heat, efficient atomization, the proper amount of air introduced in the proper manner, sufficient volume in the furnace, and sufficient time for the process of combustion.

The element of time afforded for complete combustion is important and is governed entirely by the draft in the furnace. Furnace draft should not exceed  $\frac{1}{10}$  in., and the air ports should be so designed that the adequate quantities of air will be available at this draft or even slightly less.

If higher furnace draft is used, unburned oil vapor will be drawn into the boiler tubes where the flame is immediately extinguished to form "smudge" or soot. It is particularly offensive, since it is moist and sticky and causes material damage to surfaces and materials on which it may be deposited.

**Table 14-1. Rate of Air Flow through Ports<sup>1</sup>**

By induction (natural draft). Flow per square foot of net area, air at 100°F

Furnace draft, in.	Air flow, cfm	Furnace draft, in.	Air flow, cfm
0.01	400	0.10	1,265
0.02	569	0.15	1,550
0.03	694	0.20	1,790
0.04	802	0.25	2,000
0.05	895	0.30	2,190
0.06	982	0.35	2,380
0.07	1,060	0.40	2,530
0.08	1,135	0.50	2,930
0.09	1,200	0.60	3,100

<sup>1</sup> "Smoke," Perflex Corp., Milwaukee.

to handle desired load range. This may mean wide-range burners or multiple burners.

4. Watch burners for wear caused by abrasion of ash in fuel and for carbon build-up.

5. Always protect cup of a rotary burner after it is turned off; otherwise carbon forms in the rim and spoils atomization.

6. Worn or carbonized mechanical-atomizing nozzles interfere with good combustion. Replace worn nozzles and keep them clean.

7. Many smoke troubles arise from faulty air supply. If installation is manually controlled, make sure air supply is regulated when oil flow is changed. Keep air inlet and fan blades clean. Clogged dirt and lint cut air flow, and smoke may result.

8. Smoke may be produced when starting a cold furnace. If preheating steam is not available, use light oil until furnace is hot and preheating can be used. Always start with a moderate flame, shifting to high when furnace has warmed up.

9. Watch out for the formation of carbon "mushrooms" on the walls of a cold furnace.

10. Avoid overloads. If multiple burners are installed to vary the load, be sure any burner taken out of service is removed from furnace to avoid carbon build-up. Watch out for "dribbling" when burners are shut down. If burners dribble, check the valves.

The formation of "sludge" from the heavier oils frequently causes poor atomization because of burner-tip clogging, fouling of rotary cups, and pulsation. The use of a recognized solvent is recommended in such cases.

#### **Oil and Gas.<sup>1</sup> Smoke-prevention Suggestions.**

1. Match combustion-chamber length and shape to flame length and shape.

2. Make sure that flame does not impinge on furnace walls or boiler surfaces. Such impingement increases maintenance and often causes smoke.

3. Burner installation should be able

<sup>1</sup> *Power*, September, 1947, pp. 64-68.

*Selection of Fuel.*

1. Commercial oils and gases offer little in the way of selection problems. It is essential, however, that burner characteristics be suited to the nature of the fuel burned.

2. Fuel must be supplied under pressure and temperature conditions to suit the burner.

3. Make sure that the fuel-handling system, from pipe line to storage tank right up to the burners, is designed to deliver clean fuel.

4. Be careful in mixing fuel oil from different sources. Some mixtures promote sludging.

**The Control of Smoke with Hand-fired Bituminous Coal<sup>1</sup>**

When coal is fired by hand, the volatile content is distilled off and released above the incandescent fuel. If these gases are permitted to escape, they do so in the form of smoke. They can be burned only when coal is introduced in sufficiently small quantities so that the relatively slow rate of the distillation of the volatiles takes place where sufficient temperature exists, and when sufficient oxygen is available, to enable them to burn.

Hand-firing methods to be used must be determined by the volatile content of the fuel and the combustion rate required. If frequent attention is possible, very thin firing may be satisfactory and produce but little smoke, and that of a degree of density permissible in most districts. For lower rates of combustion on lighter loads, the coking method of firing may be used to an advantage. Fresh fuel is piled in a ridge just inside the fire door, where the gases, as they are released, are drawn over the burning fuel. After the gases are consumed, the fuel may be spread over the grate and a fresh charge begun (see Chap. 23 for a more complete description).

Secondary or overfire air is of great importance in hand-firing bituminous coal. The volatile gases that are distilled off and released above the fuel bed will be consumed if sufficient oxygen is available and the temperature is high enough to support combustion; secondary air, introduced above the fire, is the source of this necessary oxygen.

Fire doors should be opened only for cleaning fires and adding fuel, and the ashpit doors should be open when operating. All control of the draft and combustion rate should be by manipulation of the uptake or stack damper.

Draft control for the hand-fired boiler is of importance. Such control, if automatic, will provide only such draft over the fire as is necessary to carry the load and effect complete combustion. Too little draft does not furnish sufficient air for complete combustion; excessive draft lowers furnace temperature and wastes heat to the stack. In extreme cases, the gases may be drawn off before they can be completely consumed to pass out the stack as smoke.

**OVERFIRE AIR<sup>2</sup>**

Overfire air may be defined as the application of air over the fire in addition to that normally applied through the fuel bed in such manner, volume, and intensity as to provide the proper turbulence and necessary oxygen to obtain complete combustion of the volatile gases and carbon from the fuel within limits of the furnace.

**Effect on Total Air Supply.** In furnaces where the air supply through the fuel bed is insufficient for complete combustion, overfire air can make up this deficiency. In furnaces where an uneconomical excess of air is used to effect complete combustion, this excess can be reduced and complete combustion effected by the introduction of

<sup>1</sup> "Smoke," Perfex Corp., Milwaukee, 1947.

<sup>2</sup> Prepared by Smoke Prevention Association of America for A Guide for Reducing Fuel Consumption in Commercial Plants, *U.S. Bur. Mines Bull.* 466, p. 41, 1947.

*definite quantities of overfire air. The total air supplied to a furnace need not be increased by the use of an overfire air system; it simply transfers the point of entry of a portion of the air required for complete combustion from below the fuel bed to the space above the bed.*

**Results of Overfire Air.** Overfire air, introduced in high-velocity jets, accomplishes two results:

1. It eliminates a deficiency of air in the furnace when it exists, as when a fresh charge of fuel has been added and the rate of release of volatiles is high.
2. It produces turbulence, when introduced at proper velocities and direction, so that gases rich in combustible are mixed with air.

**Methods Employed for Introduction of Overfire Air.** Overfire air can be introduced into a furnace by:

**1. Air-aspirating Steam Jets (Steam-air Jets).** While these involve the lowest first cost, as prime movers of air they are the least efficient, the operating cost being higher than that of electrically driven blowers. Their construction, however, is simple and rugged, and repairs can be quickly and easily made. They allow for close and easy regulation of both steam and air flow, and thus intelligent operation can somewhat reduce their unfavorable operating cost. When only turbulence is lacking, because the furnace already contains sufficient air, only steam can be used.

**2. Motor-driven Fans.** Cost less to operate because of their greater efficiency as prime movers. The savings depend on the relative cost of electricity and steam. Their first cost is higher than that of a steam-air-jet system of similar capacity.

**3. Steam-turbine-driven blowers** have characteristics similar to motor-driven blowers. They are used where electricity is not available or where there is use for the exhaust steam.

**4. Air from the Forced-draft System.** Low in cost but has low velocity and penetration. Thus its use is limited to those applications where high turbulence is not required of the jets or where the furnace is quite small.

**Pressure Required.** The minimum effective steam pressure for steam-air jets depends on furnace design and operation as well as on the design of the jets. There are steam jets operating satisfactorily on pressures as low as 5 psi. Experience indicates, however, that penetration and turbulence drop with the decrease in steam pressure, and 25 psi is about the lowest effective pressure that should be used.

Steam-air jets using pressures lower than 25 psi must be more carefully proportioned and located than those using higher pressures. Common practice employs pressures of 25 to 100 psi.

The air pressure required for fan jets depends upon the following independent factors:

1. Quantity of air to be delivered per nozzle
2. Penetration or turbulence required
3. Furnace-gas velocity.

The pressures in general use range from 6 to 15 in. water at the nozzles. Lower pressure fan jets are effective only in special cases.

**Amount of Overfire Air to Supply.** General practice employs about 10 per cent of the air theoretically required for the combustion of the fuel as overfire air. Where great variations in load occur or where large quantities of volatile are periodically released, as in hand-fired furnaces, quantities as high as 25 per cent may be required. Where the excess air in the furnace is difficult to control and turbulence is the main requirement, quantities as low as 3 per cent, at relatively high velocities, may be used.

**Location of Overfire Jets.** General practice employs the following arrangements:

1. *Front-wall Jets.* These are installed in the front wall of the furnace and directed toward the rear or bridge wall, parallel to the side walls, and pitched downward.

2. *Rear-wall Jets.* These are located in the rear wall or bridge wall of the furnace and blow toward the front wall. They are otherwise similar to the front wall jets, except that the pitch is not so pronounced. When using steam-air jets in the bridge wall, it is advisable to arrange the steam nozzles on a header that can be readily removed for servicing while the boiler is in operation.

3. *Cross-fire Jets.* This arrangement consists of a single jet at each of the front or rear corners of the firebox. The two jets are directed to cross over the center of the grate. Two modifications of this arrangement are advised: (a) On *traveling grates* using an ignition arch, the crossing point should be under the arch and about 12 in. from the nose of the arch. (b) On *single-retort* underfeed stokers, the cross jets are installed in the front wall instead of in the corner, so that each jet enters the furnace at 25 to 30 per cent of the firebox width from the center line of the retort. They meet over the center of the retort about 6 in. above the fuel bed. An additional jet, located over the center line of the retort and directed parallel to it, is recommended in some cases.

4. *Four-corner Tangential Jets.* This arrangement consists of one jet in each corner so directed as to be tangential to a circle at the center of the grate and to give a rotating action to the gases in one continuous direction. The diameter of the circle is about one-third of the width of the firebox.

#### General Rules for Jet Design.

1. Jet streams should enter the yellow portion of the flame.
2. Jets lose effectiveness when installed too high; they may cause clinkering when they are too close to the fuel bed.
3. Jets are commonly installed 16 to 30 in. above the grate line and given a slight pitch downward.
4. Jets introducing air counterflow to the gas stream produce the most turbulence.
5. Jet streams should not impinge on the fuel bed or on the brickwork of the side walls.
6. Steam jets should be made of monel metal, stainless steel, or a similar material that will resist cutting, since jets made of ordinary steel soon cut out and admit a greater amount of steam than is necessary.
7. When steam jets are used intermittently, a trap should be used in the steam line to remove condensation.
8. Air jets near the face of brickwork should be made of high-heat-resisting metal in order to stand the temperatures of radiation and convection from the hot brickwork.
9. To eliminate objectionable noise produced when the air inlets to the jets are open to the air in the boiler room, the air intake may be piped from the stoker wind box, or from air channels in the settings.
10. On installations where the release of volatiles is periodically high, as in hand-firing, a quick-opening valve controlling all the jets of a furnace should be conveniently located at the front of the boiler.
11. Special arrangements can be provided to turn on the jets automatically when the fire doors are opened. An electric eye can also be used for this purpose.

#### Jets for Turbulence in Spreader-stoker Firing<sup>1</sup>

In spreader-stoker firing, it is axiomatic that the fuel bed must be maintained in a thin, active, and fully aerated condition. On the other hand, if the air flow through the furnace is excessive, the furnace temperatures will be reduced, and incomplete combustion is likely to be experienced. Sufficient air can usually be supplied through the thin fuel bed, so that the objective of jets becomes one of mixing or turbulence

<sup>1</sup> MEISSNER, H. G. and M. O. FUNK, Use of Jets to Produce Turbulence in Spreader Stoker Firing, *Combustion*, September, 1944.

rather than of additional air. Air jets for spreader stokers should thus be designed for maximum velocity rather than volume, so that the quantity of added overfire air will be held to a minimum. An estimate of the overfire air desirable with spreader stokers places it at a maximum of 5 to 6 per cent of the total air requirements.

Steam jets have often proved effective in creating turbulence and have the advantage of introducing no additional air. While they are the most expensive to operate, the correct arrangement of either steam or air jets will usually increase the overall efficiency or capacity of the boiler sufficiently to more than balance the cost of operation.

When air or air-steam jets are used, the quantity of air must be carefully considered so as not to exceed 5 to 6 per cent of the total air required. A pressure of approximately 30 in. is necessary for proper turbulence at this quantity.

Four tangential jets, located at the four corners of the furnace, proved most effective as regards both smoke and cinder reduction (see Table 14-2).

**Table 14-2. Relative Effectiveness of Various Air-Jet Arrangements<sup>1</sup>**

(On a basis of smoke and cinder emission, using Ohio coal, 115 psi saturated steam. Note that arrangement 6 gave the best performance as regards both smoke and cinder emission)

Arrangement	Relative steam consumption	Relative emission	
		Smoke	Cinders
1. Two $\frac{1}{8}$ -in. steam nozzles at rear corners, each 34 in. above grate, inclined toward grate . . . . .	1.9	2 16	1 59
2. Four $\frac{1}{8}$ -in. tangential steam nozzles at four corners of furnace, each 34 in. above grate, inclined toward grate . . . . .	1.0	1 49	1 94
3. Same as arrangement 2 except that nozzles were $\frac{1}{4}$ in. in diameter . . . . .	3.8	1 71	1 15
4. Three $\frac{1}{8}$ -in. steam nozzles equally spaced across front of furnace, 6 ft 6 in. above grate, inclined toward grate . . . . .	2.9	4 51	1 43
5. No nozzles in furnace . . . . .	1.0	5 60	1 82
6. Four $\frac{1}{8}$ -in. tangential steam nozzles at four corners of furnace, each 34-in. above grate, horizontal . . . . .	3 8	1 0	1.0
7. Eight $\frac{3}{8}$ -in. steam nozzles, four in each side wall, 5 ft above grate, inclined toward grate . . . . .	4 6	1 87	1 70

<sup>1</sup> MEISSNER, H. G., and M. O. FUNK, Use of Jets to Produce Turbulence in Spreader Stoker Firing, *Combustion*, September, 1944.

The general effect of steam or air jets, properly used and proportioned with spreader stokers, is to reduce cinder carry-over and smoke and to increase the boiler efficiency by as much as 1 to 3 per cent when furnace conditions are otherwise satisfactory.

**Table 14-3. Relative Operating Costs of Various Types of Jets<sup>1</sup>**

	Static pressure, in. H <sub>2</sub> O	Per cent of total combustion air or steam required	Relative operating cost
Fan . . . . .	5	12 0	1 0
Fan . . . . .	10	9 1	1 5
Fan . . . . .	30	5 7	2 9
Steam jet, no entrained air . . . . .		1 1	3 6
Steam-air ejector . . . . .		0 5	1 8

<sup>1</sup> MEISSNER, H. G., and M. O. FUNK, Uses of Jets to Produce Turbulence in Spreader Stoker Firing, *Combustion*, September, 1944.

Stoker firing produces considerably coarser ash than pulverized-fuel firing and thus presents entirely different problems of ash or dust collection. Table 14-5 shows a typical pulverized sample to contain some 77 per cent below 325 mesh; whereas the stoker sample has only about 24 per cent below 325 mesh. The pulverized sample had only 2 per cent larger than 150 microns, as compared with 37 per cent with the

stoker. From various samples, Best concludes that pulverized ash will range from 65 to 85 per cent less than 325 mesh, stoker ash 15 to 40 per cent less than 325 mesh.

**Table 14-4. Steam Flow through Various-sized Nozzles<sup>1</sup>**  
(Pounds per hour)

Pressure, psi	Nozzle diam, in.					Pressure, psi	Nozzle diam, in.				
	1/16	3/32	1/8	5/32	3/16		1/16	3/32	1/8	5/32	3/16
100	18	40	71	112	162	250	41	93	166	259	
150	26	58	102	160	231	300	49	111	197	308	
200	33	75	134	210	300						

NOTE: Values are for saturated steam; flow with superheated steam is somewhat lower.

<sup>1</sup> MEISSNER, H. G., and M. O. FUNK, Uses of Jets to Produce Turbulence in Spreader Stoker Firing, *Combustion*, September, 1944.

**Table 14-5. Size Comparison: Pulverized Coal Ash vs. Underfeed Stoker Ash<sup>1</sup>**

Size, microns	Per cent of size indicated		Size, microns	Per cent of size indicated	
	Pulverized-fuel ash	Stoker ash		Pulverized-fuel ash	Stoker ash
+150	2 0	37 0	20-30	16 0	6 5
100-150	3 0	13 0	15-20	11 0	3 3
60-100	8 0	17 0	10-15	14 0	2 7
40-60	10 0	11 0	7 5-10	9 0	1 3
30-40	10 0	7 0	-7 5	17.0	1 2

<sup>1</sup> BEST, PHILIP F., "Combustion Ash Collection for the Small Power Plant," ASME annual meeting, paper 48A-55, 1948.

**Air or Gas Loading.** The loading of air or gases is defined as the grains of solid particles per cubic foot of gas.

Best concludes that stoker firing generally produces about 1.5 grains of dust per cu ft of gas; pulverized fuel firing 2.5 grains, both corrected to 32°F. In pounds of dust per 1,000 lb of gas, this means 2.6 for stoker-fired installations and 4.4 for pulverized-fuel firing.

Loading is affected by so many factors, such as boiler rating, draft conditions, various elements of design, fuels, and fuel conditions, that any such figures on loading should be considered as relative approximations only.

Cyclone separators are not critical as to dust loading. Thus, for a given installation, all other factors equal, if the dust loading of the inlet gas is doubled, the amount of gas both collected and escaping will be doubled. Electric and ultrasonic precipitators are critical as to loadings, the maximum practical loading for electric precipitators being 25 grains per cu ft.

The ASME specifies a maximum of 0.30 grains per cu ft of total solids in their model smoke law (Pittsburgh allows 0.75 grain).

## INDUSTRIAL DUST AND AIR POLLUTION

### Characteristics of Fine Particles

Dust is limited to solid particles larger than 1 micron, with smaller particles being classified as fumes, smoke, etc. There is no practical limit to the upper dimension, as the heavy industrial dusts graduate into cinders which may be of any size.

While some dusts, such as portland cement, are more or less homogenous as to particle size and density, this is the exception rather than the rule, as most dusts are composed of a complex, and widely varying, mixtures of sizes, often ranging from a fraction of a micron to cinders.

**Specific Gravity.** The specific gravity of dusts commonly collected ranges from 0.5 to 8.0. Here again the individual particles may all be of the same, or approximately the same, specific gravity, or they may be a mixture of materials of several different gravities. This is important, because it enters into the design of such separators as cyclones and has a direct relation to the velocity of fall of emissions from stacks.

**Shape of Particles.** Dust particles may be in almost every conceivable shape. While for purposes of calculation of weight, etc., they are usually assumed to be spherical, this is seldom the case, as they may consist of flat disks, conchoidal fractures, ovoids, etc. The shape affects their agglomeration on collision.

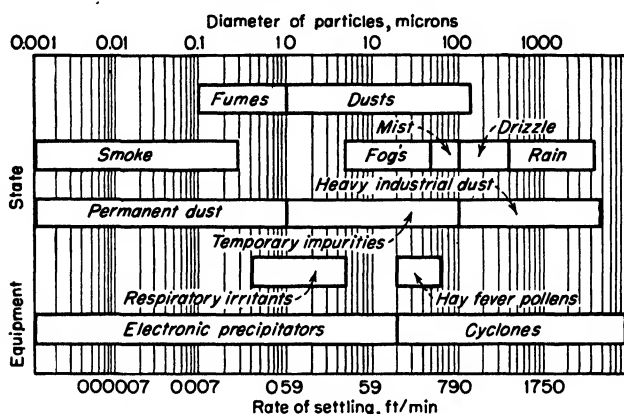


FIG. 14-3. Classification of common atmospheric impurities and range of apparatus. (Christie, A. G., "Industry and Power.")

**Adhesive Properties.** Depending largely upon the content of moisture, tar, etc., different dusts have different degrees of adhesion ranging from a purely mechanical interlocking to definite stickiness. This frequently complicates the problem of final removal from collecting surfaces.

#### Settling Velocity of Particles<sup>1</sup>

Buell gives the following formula for calculating the settling velocity of fine particles:

$$v = \frac{2}{9} r^2 \frac{(p_1 - p_2)g}{n}$$

where  $v$  = settling velocity

$r$  = radius of ball-shaped particle

$p_1$  = mass density of particle (in metric units numerically equal to the specific gravity)

$p_2$  = mass density of the gas

$g$  = acceleration due to gravity

$n$  = viscosity of the gas

Since  $p_2$  is negligible in comparison with  $p_1$ , for practical purposes the settling velocity will be proportional to

$$r^2 \times p_1$$

For example, using this simplified formula, a particle of 10 microns and a specific gravity of 2 will be found to have the same settling velocity as a particle of 14 microns

<sup>1</sup> Buell Engineering Co., New York.

and a specific gravity of 1. This is because

$$10^2 \times 2 = r^2 \times 1 \quad \text{and} \quad r = 14.14$$

These formulas are commonly used for computing settling time or effectiveness in cyclone separators.

**Falling of Dust Particles.**<sup>1</sup> The travel and falling of dust particles often causes a major nuisance in or near a plant. The amount of cinders or other dust which falls within a given distance of the stack is affected by particle size and density, stack height, and wind velocity, as shown in Fig. 14-4.

An approximate relationship is given by the formula

$$\text{Travel, miles} = 2.8 \frac{(\text{wind velocity, mph}) \times (\text{stack height, ft})}{(\text{particle size, microns})^2 \times (\text{specific gravity})}$$

It will be noted that the travel in miles varies inversely as the specific gravity of the material. This factor is commonly neglected in the use of charts such as Fig. 14-4.

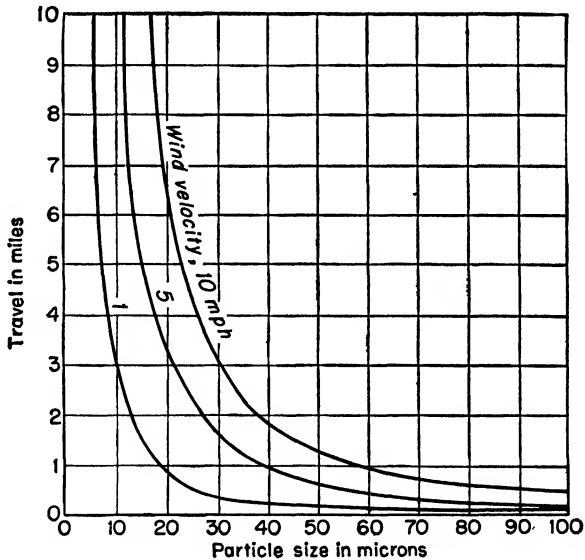


FIG. 14-4. Distance of travel of dust particles from 200-ft stack. (B. F. Sturtevant Company.)

As specific gravity of common materials may vary from 0.5 to 8, the magnitude of the resultant error is obvious. Thus, while Fig. 14-4 is computed for a specific gravity of 2 (the usual assumption for fly ash from coal), new charts should be prepared for other gravities and conditions.

It should also be noted that, as ability to stay aloft is inversely proportionate to the square of the particle size, dusts composed of a mixture of sizes may be expected to fall progressively, the largest particles nearest the plant, and vice versa.

Under actual conditions, interference of buildings, hills, etc., will produce eddy currents and downdrafts which will materially modify the distance of particle travel. Areas of water are particularly prone to cause such downdrafts. The formula does, however, indicate the effect of various factors qualitatively and their importance.

<sup>1</sup> "What We Make," Condensed Catalog & Engineering Data, No. 500, p. 168, B. F. Sturtevant Co., Hyde Park, Boston, Mass., 1945.



**Table 14-6. Distance of Dust Travel from 200-ft Producing Stacks in 5-mile Wind**

(Based, on dust sizes lost by collectors in Tables 14-5)

Distance from stack	Per cent of total dust falling within distances indicated	
	Pulverized fuel	Stoker firing
300 ft . . . . .	0 0	0.5
500 ft . . . . .	0 0	2.4
1,000 ft . . . . .	0 0	16 7
2,500 ft . . . . .	0 0	35.8
4,000 ft . . . . .	0 0	45 0
1 mile . . . . .	0 0	52 0
2 miles . . . . .	2 3	70 0
5 miles . . . . .	5 7	80 4
10 miles . . . . .	18 2	89 9
Over 10 miles . . . . .	81 8	10.1

<sup>1</sup> BERT, PHILIP F., "Combustion Ash Collection for the Small Power Plant," ASME Paper 48-A-55, annual meeting, 1948.

**Table 14-7. Standard Screen Sizes<sup>1</sup>**

U. S. Bureau of Standards			W. S. Tyler Co. screen		
Mesh No.	Microns	Openings, in.	Mesh No.	Microns	Openings, in.
10	2,000	0 0787	9	1,981	0 0780
12	1,680	0 0661	10	1,651	0 0650
16	1,190	0 0469	14	1,168	0 0460
20	840	0 0331	20	833	0 0328
30	590	0 0232	28	589	0 0232
40	420	0 0165	35	417	0 0164
50	297	0 0117	48	295	0 0116
60 <sup>a</sup>	250	0 0098	60	246	0 0097
70	210	0 0083	65	208	0 0082
80	177	0 0070	80	175	0 0069
100 <sup>a</sup>	149	0 0059	100	147	0 0058
140	105	0 0041	150	104	0 0041
170	88	0 0035	170	88	0 0035
200 <sup>a</sup>	74	0 0029	200	74	0 0029
230	62	0 0024	250	61	0 0024
270	53	0 0021	270	53	0 0021
325 <sup>a</sup>	44	0 0017	325	43	0 0017

<sup>1</sup> B. F. Sturtevant Co., Hyde Park, Mass, Catalog 500.

<sup>a</sup> Screen sizes used in ASME Power Test Code for Dust Separating Apparatus.

#### Summary of Fly-ash Emission and Characteristics from Various Types of Equipment

**Spreader Stokers.** Usual fly-ash emission 1.0 to 2.0 grains per cu ft. Some few installations below this average; others as high as 2.5 grains per cu ft. Size consist, about the same as underfeed stoker, about 35 per cent passing 325-mesh screen. Variations in quality about plus or minus 10 per cent. Rate of stoker firing has relatively little effect on rate of fly-ash emission in grains per cubic foot. Probable ratio of maximum to minimum fly-ash emission is 2:1 between 10 lb of fuel per sq ft of grate and 50 lb. Of the total ash, 20 to 25 per cent may be stack-emitted.

**Underfeed Stokers.** Usual emission about 1.5 grains per cu ft. Fly ash is much more coarse than with pulverization, approximately 37 per cent being above 150 microns as against 2 per cent with pulverization. Rate of firing has profound effect on rate of emission; ratio of emission as between low firing and maximum firing being as high as 10:1. About 15 per cent of the total coal ash may be emitted.

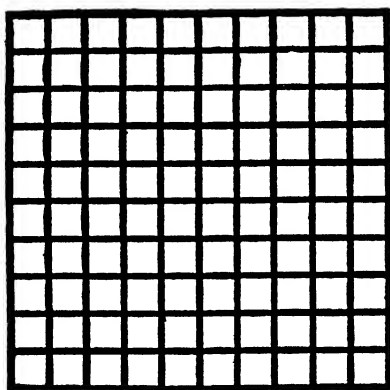
**Pulverized-coal Firing.** Usual emission about 2.5 grains per cu ft of flue gas. Usually very fine, with only about 15 per cent exceeding 60 microns, and only half of this above 100 microns. Under the worst conditions, pulverized-coal burners may discharge up to 70 per cent of the ash in the coal to the stack. Usual range is 40 to 70 per cent with slag-tap furnaces in the lower range, dry bottoms in the upper.

**Traveling Grates.** Rate of emission is reasonable to about 20 to 25 lb fuel per sq ft of grate; beyond this point the amount increases at a very rapid rate.

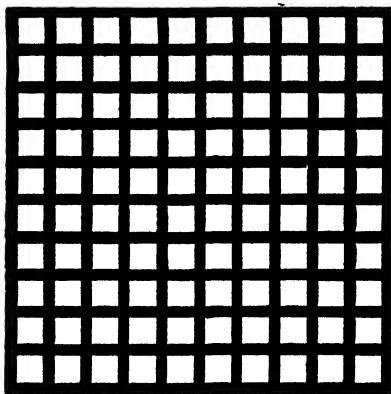
**Determination of Dust Emission.** An accurate determination of dust emission is very difficult. The common method of observing the discharge of chimney and other dusts and judging the density by comparison with a Ringelmann chart has been largely discredited. Dr. Marks has shown that such a determination is influenced by the nature of the sky behind, and to an even greater extent by the diameter of the stack.

A large diameter with only moderate dust may diffuse light to such an extent as to appear several shades darker than if the stack was smaller. An additional obvious limitation of the Ringelmann chart is the fact that it cannot be used at night.

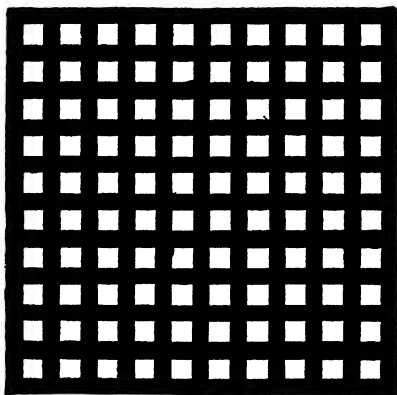
Dusts from pulverized coal are considerably finer than those from stokers. These dusts are more readily visible than coarser dusts of the same actual loadings because of the larger exterior surface areas exposed to the light. Thus the finer dusts are apt to appear dirtier and to draw more complaint.



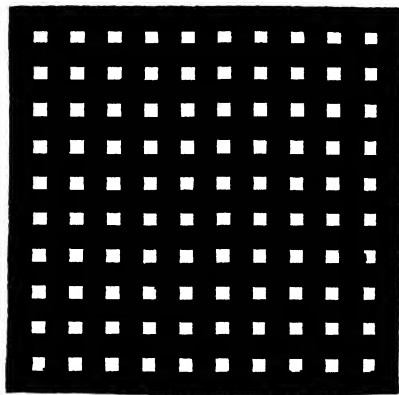
1



2



3



4

FIG. 14-5. Ringelmann chart for determining smoke density.

Recorders are available based upon the use of the density of light passing through the dust-laden gas stream, and received on a light-sensitive cell or "electric eye." Such devices could be more widely adopted to advantage.

#### REASONS FOR THE COLLECTION OF DUSTS

There are four major reasons for wanting to separate dust and fumes from their carriers: (1) as an abatement of a nuisance with resultant civic betterment, protection of machinery equipment and buildings, elimination of damage claims, improvement of employee morale, and increase in production efficiency; (2) for the recovery of

Table 14-8. Typical Dust-emission Regulations

	Grains/cu ft		Lb/1,000 lb flue gas	Approx per cent fuel fired
	300°F	500°F		
Philadelphia	1 072	0 85 <sup>a</sup>	2 82	3.5
Pittsburgh	0 946	0 75 <sup>a</sup>	2 49	3 1
Baltimore	0 946	0 75 <sup>a</sup>	2 49	3 1
Peoria, Ill	0 505	0 40 <sup>a</sup>	1 32	1 7
Detroit	0 379	0 30 <sup>a</sup>	0 99	1 2
Cincinnati	0 324	0 257	0 85 <sup>a</sup>	1.1

<sup>a</sup> Figures specified in ordinance; others are calculated.

Table 14-9. Comparison of Various Municipal Smoke-prevention Laws<sup>1</sup>

City	Max No. of units allowed <sup>a</sup>					Minutes and density allowed for cleaning, etc. <sup>b</sup>	Dust loading, grains/Mcf at 60°F and 29.92 in. Hg
	Ringelmann No.						
	1	2	3	4	5		
Atlanta	d	d	0-900	0-613	0-767	8 min No. 3 and over/hr	785 @ 12 % CO <sub>2</sub>
Buffalo... .	d	d	0-30	0-40	0-50	2-6 min No. 3 /day	Nuisance
Chicago	d	d	0	0	0	6 min No. 3/hr	Nuisance (350)
Cincinnati <sup>c</sup> ..	d	d	d	0-4	..	6 min/day	480 @ 50 % excess air
Cleveland.	d-10	0-d	0-54	0-48	0	...	2,150 of 50 mesh and over
Columbus .	d	32	0-12	0-16	0-20	6 min No. 3 and over	480 @ 12 % CO <sub>2</sub>
Detroit. .	d	16	0-18	0	0	12 min No. 3 and over	588
District of Columbia	d	d	0	0	0		Nuisance
Hudson County, N.J	d	24-32	24-30	32-40	40-50		Nuisance
Massachusetts.	d	d-50	9-30	10-40	15-50	10 min No. 3 and over	Collectors on mechanical draft
Pittsburgh .	d	0-2	0-3	0-4	0-5	9 min No. 2 or 6 min No. 3	1385 total and 370 over 325 mesh @ 50 % excess air
St. Louis ..	d	0-2	0-3	0-4	0-5	9 min No. 2 or 6 min No. 3	Same as Pittsburgh
Toledo ... .	d	d-16	0-12	0-16	0-20	12 min No. 3 and over	480 @ 12 % CO <sub>2</sub>
Wyandotte, Mich. <sup>c</sup>	d	6-20	0-225	0	.	.	Nuisance or 400 of 50 micron or larger
ASME model law . . . .	d	16	0	0	0	12 min No. 3 and over	480 @ 12 % CO <sub>2</sub>
Stoker Manufacturers Assoc.	d	d	0-3	0	0	9 min No. 3 or 6 min No. 4-5	Nuisance
Salt Lake City..... ..	d	d	3	4	5	6 min No. 3 and over	

NOTE: This table is necessarily very rough and is intended merely as an indication of the ordinances. Where a range is given, the less dense smoke usually refers to stationary equipment; the denser smoke to railroad and marine. Local ordinances should be consulted for exact definitions. Where a zero is shown under a Ringelmann number, any emission of any duration of this density constitutes a violation.

<sup>1</sup> Condensed from *Coal Heat*, August, 1947.

<sup>a</sup> The smoke unit equals 1 min of No. 1 smoke, etc. (thus 2 min of No. 2 smoke = 4 units).

<sup>b</sup> Minutes and densities shown are usually those for cleaning fires. Provision is usually made for additional time for breakdowns, etc.

<sup>c</sup> Umbrascopes scale.

<sup>d</sup> Not prohibited.

commercially valuable by-products; (3) for the direct collection of powdered products in the process industries; and (4) for the cleaning of air or other gases for subsequent use.

**Occupational Diseases.** Silicosis and asbestosis are well-known diseases having their origin in the irritation of industrial dust. Metal dusts such as lead, magnesium, cadmium, and their compounds are toxic.

In general, dusts and fumes between 0.4 and 5 microns in size are considered most likely to cause respiratory irritation and lung damage. Hay-fever pollen approximates 20 to 60 microns. Thus, if collection equipment is being installed with an alleviation of one or both of these conditions in mind, an examination of its effectiveness, or removal efficiency, at these ranges is in order.

**Fire and Explosion Hazard.** Any combustible dust which will oxidize rapidly will, with proper size and concentration conditions, cause a potential explosion or fire hazard. Special design precautions are necessary with this group, which includes all agricultural dusts, coal dust (except anthracite), wood dust, aluminum dust, etc. (see Table 18-19 and accompanying material).

**ASME Model Smoke Ordinance.** In 1940, the ASME appointed a Model Smoke Law Committee. After receiving the cooperation of many organizations, including the Smoke Prevention Association of America and the Stoker Manufacturers Association, they released (May, 1949) an information bulletin containing example sections for a smoke-regulation ordinance. This is intended as a guide for ordinances of this type. It has already been used as a basis for laws by more than 100 cities in adopting or changing their ordinances. (It is suggested that those interested in a smoke prevention measure secure a copy from the American Society of Mechanical Engineers, New York.)

Emission limitations considered by the committee to be appropriate for an industrial city restrict emission from all fuel-burning equipment, internal-combustion engines, and open fires to the density of a No. 2 Ringelmann chart. Exceptions are allowed up to a No. 4 Ringelmann density for periods aggregating 4 min in any 30 min; or a top of No. 3 Ringelmann density for periods aggregating 3 min in any 15, when building a new fire or when breakdown occurs.

Emission of dust in the gases is limited to 0.85 lb per 1,000 lb of gas adjusted to 50 per cent air for products of combustion. Exceptions allow a dust collector of 75 per cent efficiency if constructed before the effective date of the ordinance; 85 per cent if constructed afterward. Dust limitations can be waived during breakdowns.

### Misconceptions and Illusions in Smoke-prevention Measures

K. C. Richmond<sup>1</sup> very properly points to a number of fallacies in connection with smoke prevention, among which are:

1. Merely passing a smoke ordinance does not automatically reduce or prevent smoke.

2. Smoke abatement is not the only objective; it is air purification. It is the unseen gases and fumes from all sources with which we are concerned; not coal smoke alone.

3. So-called "soot fall" records (more correctly "dust fall") fail to tell the entire story, because the dust may come from a very considerable distance. Some of the dustiest towns in this country are in Oklahoma, Texas, and New Mexico, where little or no coal is used.

4. Smoke may be caused by the equipment and the manner in which it is maintained and operated, as well as by the fuel.

5. The diesel engine by no means eliminates air pollution; its exhaust fumes should not be discounted (see *Diesel Power*, March, 1947, pp. 49, 62).

<sup>1</sup> RICHMOND, K. C., *An Analysis of Smoke Ordinance Regulations*, *Coal Heat*, August, 1947, p. 9.

6. Above all, the effectiveness of any ordinance is coupled with the fearlessness of its enforcement.

### EQUIPMENT AVAILABLE FOR COLLECTING FINE DUSTS

The rapidly increasing interest in air purification due to widespread interest and action in smoke abatement has resulted in the availability of many different devices for the collection of fine dusts and fumes.

These range from settling tanks, where the velocity is so slowed by available space as to cause the larger particles to drop out, to cyclonic collectors with both single and multiple tubes, electrical precipitation, and, more recently, ultrasonic separation. In addition a wet or scrubbing process finds considerable acceptance in England, where smog is a major problem.

Each of these systems has its own advantages and disadvantages, and an attempt has been made to summarize these in Table 14-10. Usually an advantage for one gas might be a disadvantage for another, so that it is necessary to study each problem individually with particular reference to the factors discussed in this section, committing the design to any specific equipment.

**Table 14-10. Relative Advantages and Disadvantages of Various Dust Collectors**

Type of collector	Advantages	Disadvantages
Cyclone collectors (centrifugal):		
Single-cone type	Good efficiency on larger particles (99% on 30 microns and larger) Constant draft resistance. Efficiency constant on all dust loadings	Relatively high draft resistance. Low efficiency on smaller particles, vanishing to negligible results below about 2 microns
Multiple-cone type.....	Efficiency on small particles better than single cones. Constant draft resistance and high dust storage	Inlets must be very carefully designed and proportioned for proper load distribution
Electrical precipitators (Cottrell)	Very high efficiency on certain small particles. Low draft resistance Advantageous for fumes (will handle cigarette smoke with particle sizes of some $\frac{1}{10}$ micron)	Tendency to fail to hold certain conductive particles. Low efficiency on larger particles. Tends to generate ozone and oxides of nitrogen; dangerous if air is to be reused. High first cost. Principal problem to prevent loss of dust during rapping
Combinations of electrical precipitators and cyclones:		
Multicone ahead of electric precipitator	Removes coarse dust ahead of electrical precipitator. Covers broader range of particle size	Increases pressure drop and operation expense. Does not help loss of dust during rapping
Electric precipitator ahead of multicone	Removes coarse particles and agglomerated fines missed by electric precipitator, also fine dust discharged during rapping	Increased pressure drop and operation expense. Precipitator must be exposed to entire dust loading
Ultrasonic .....	Principle too new to appraise results properly	
Screen-type cloth filter ...	Low first cost	Increasing resistance with dust accumulation. Good only for low-temperature separation
Wet washing.....	.....	Costly. High maintenance. Requires large ground area. May emit smudge

### Cinder Traps

The simplest and lowest cost device for reducing fly-ash emission is the cinder or dust trap. This type of unit depends largely on the combination of a change in direction and lowered velocity to remove the solid particles from the gas. In construction,

they range from simple enlarged elbows or tees in the gas flow with collecting boots or hoppers, to more elaborate baffled chambers. The draft loss is low, usually only a few hundredths of an inch. The efficiency is also low, probably in the range of 20 to 30 per cent. They are effective only on the larger components of the flue gas. Thus, while they would often prove adequate for removing a cinder or large particle nuisance in the immediate vicinity of the stack, they have but little application to real smoke or fume abatement.

When cinder traps are equipped with interior baffles, their efficiency is increased to probably 50 to 60 per cent. Again, however, their only real effectiveness is with the larger particles. The draft loss increases to 0.1 to 0.2 in., which is still sufficiently low for *some* natural-draft applications. This type of collector is usually called a "low-draft-loss" collector.

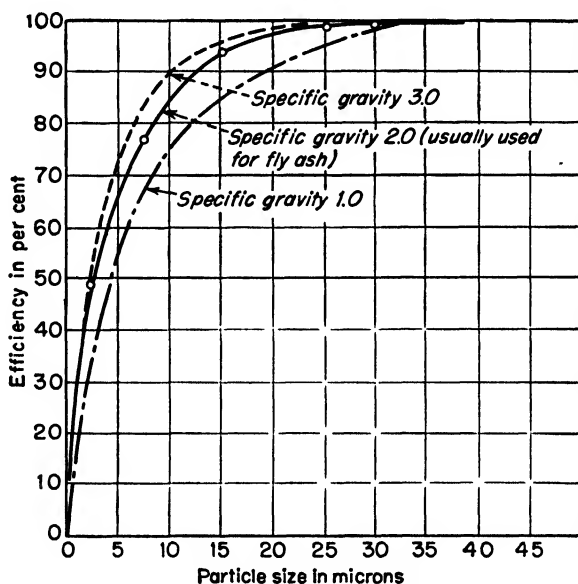


FIG. 14-6. Fractional efficiency of cyclone collector for materials of three specific gravities. NOTE: The specific gravities of dusts commonly collected may range from 0.5 to 8.0. It is thus important to know the gravity before attempting an approach to the efficiency of collection. (Buell, "Engineered Efficiency in Dust Collection and Recovery," 1947:)

### Cyclone Separators

Cyclone separators depend upon centrifugal force to project the dust particles tangentially out of the gas stream. It is thus evident that the efficiency of this type of separator will depend upon the velocity of the gases flowing through the separator as related to their tangential effect. Actually efficiency will vary as the square of such tangential effect and inversely as the square of the radius. As a result, large cyclones, when installed as single units, such as are necessary for commercial volumes of gas, usually have high draft requirements. Further, the smaller the particle size or weight the less the effect of any given tangential force, thus the greater efficiency of dust removal is accomplished with the larger sized particles. Figure 14-6 shows fractional efficiency for various particle sizes.

Actually few dusts are ever composed of particles of uniform size or even weight.

They are composites of graduated size. Thus a consideration of the collection of material with a separator of this type must be calculated from a size-consist analysis of the material to be handled. The final composite picture of the removal of each size component separately is the only way to evaluate properly the effectiveness of such separators.

**Table 14-11. Relative Minimum Tangential Velocities Necessary to Separate Dust Particles in Cyclonic Collectors<sup>1</sup>**

(Body of table shows relative minimum velocities in feet per second)

Particle size, microns	Diam of collector, ft					
	0.5	1.0	2.0	4.0	6.0	12.0
100	...	...	0 8	1 6	2 4	4 8
50	0.8	1 7	3.2	6 0	10 0	20 0
20	5	10	20	40	60	120
10	20	40	80	160	240	480
5	80	160	320	640	960	2,000

<sup>1</sup> From "Multiclones," Western Precipitation Corp., Los Angeles.

**Table 14-12. The Centrifugal Separating Force in Circular Gas Streams<sup>1</sup>**

Diam of gas path	Separating force (gravity = 1)	
	40 fps velocity	80 fps velocity
20 ft	5 times gravity	20 times gravity
5 ft	20 times gravity	80 times gravity
1 ft	100 times gravity	400 times gravity
6 in.	200 times gravity	800 times gravity
3 in	400 times gravity	1,600 times gravity

<sup>1</sup> From "Multiclones," Western Precipitation Corp., Los Angeles.

**Separation efficiency for various particle sizes**, as cited by a leading manufacturer (Buell Engineering, New York) is as follows: particles 0 to 5 microns, 49 per cent efficiency; 5 and 10 microns, 76 per cent efficiency; 10 and 20 microns, 93 per cent efficiency; 20 and 30 microns, 98 per cent efficiency; over 30 microns, 99 per cent efficiency.

**Example.** An example of the use of this grading to obtain the actual operating effectiveness for a given sample of dust follows:

- Assuming that the size consist of a 100-g sample is (by analysis): 0 to 5 microns, 8.95 g; 5 to 10 microns, 15.99 g; 10 to 20 microns, 21.00 g; 20 to 30 microns, 28.03 g; and above 30 microns, 26.03 g; total 100 g.

**Table 14-13. Collection Efficiency of Multicone Separator (Per cent)**

Micron sizes. .	+5	+10	+20	Total
Fly ash. . . . .	89	97	99	80
Portland cement.	99	95	99	83
Lime-kiln dust .	96	98	99	95
Bauxite calciner	99	99	99	99

NOTE: The percentages of materials above 5 microns were fly ash 72 per cent, cement 74 per cent, lime-kiln dust 80 per cent, and bauxite 88 per cent.

two other tests, to illustrate the meaninglessness of accepting or using a blanket or over-all efficiency figure as applied to cyclone collectors, when composite material is to be fed.

**Factors in Cyclone Design.** The efficient functioning of any dust-separating cyclone, large or small, is critically dependent upon a uniform nonturbulent flow to

- Then the calculated efficiency of collection would be

$$\begin{aligned}
 8.95 \times 49\% &= 4.39 \text{ g} \\
 15.99 \times 76\% &= 12.15 \text{ g} \\
 21.00 \times 93\% &= 19.53 \text{ g} \\
 28.03 \times 98\% &= 27.47 \text{ g} \\
 26.03 \times 99\% &= 25.77 \text{ g} \\
 \text{Total} &= 89.31 \text{ g}
 \end{aligned}$$

- The total efficiency is thus 89.3 per cent. (The actual test efficiency in this case was 90 per cent.)

The efficiency of this same cyclone operated at 79.5 per cent (when a more

the inlet port. If any bend in the duct is adjacent to the inlet, straightening vanes should be installed in the elbow to maintain uniform dust distribution. Where several cyclones are to be operated in parallel, a split-duct manifold should be used.

Proportions should be such that an efficient vortex is created by which the dust-free gas leaves the collector.

Conical section should be such as to permit the gas and dust particles to gain velocity through their spiral downward path, to discharge the dust properly into the dust chamber, and to create a powerful vortex.

Turbulence of the counterflow air streams should be avoided by proportioning and dimensioning, since such turbulence materially reduces efficient separation.

Direct impingement of the dust-laden blast on parts of the device interposed into the air stream should be avoided.

**Resistance.** Draft resistance through a single cyclone is an important factor as it is one of the determinants in the efficiency of separation. It depends entirely on design but may reach as high as 2.5 in. water pressure.

**Aerodyne Single-cone Collector.** In order to increase the efficiency of the larger cyclones and to decrease the disadvantage of the high flow resistance of multicell units, Aerodyne<sup>1</sup> offers a collector of special design in size ranges from 1,500 to 500,000 cfm.

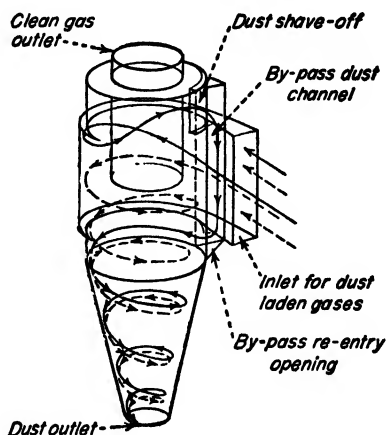


FIG. 14-7. Principle of operation of van Tongeren single-cyclone separator. (Buell Engineering Co., Inc.)

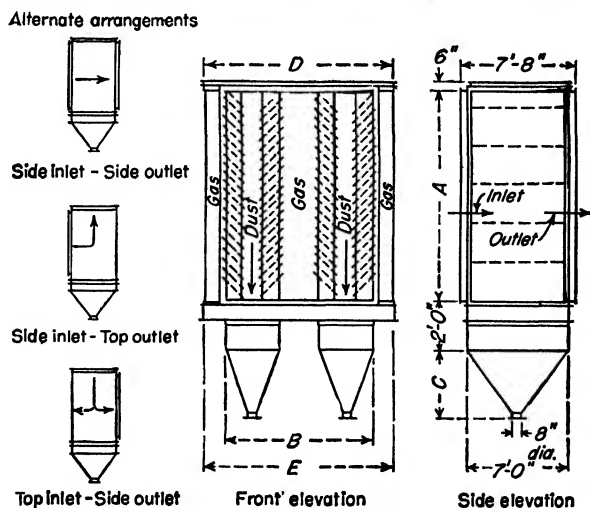


FIG. 14-8. General arrangement of Aerotec multiple-tube collector. (Aerotec Corporation, Greenwich, Conn.)

The filter surface consists of a specially slotted sheet bent in the form of a cone. The air or gas to be cleaned is passed at high velocity over this surface, and, because of

<sup>1</sup> Aerodyne Atlantic Corp., New York.



the form of the slots, aerodynamic forces are set up with the resultant force on the dust particles in a direction away from the cone face. According to Aerodyne, this force keeps the dust particles suspended in the form of a thin dust layer immediately in front of the filter surface while the clean air escapes through the slots. The dust layer is carried at high speed to the outlet end of the cone, where it is continuously withdrawn, together with a small percentage of the air or gases, into a secondary circuit. The concentrated dust mixture in this secondary circuit is then passed

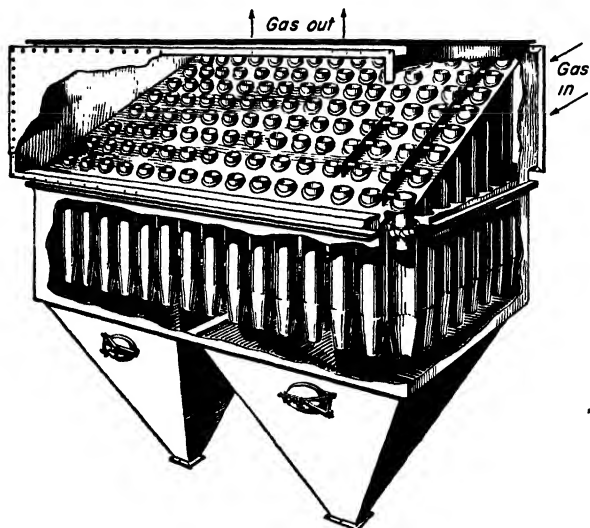


FIG. 14-9

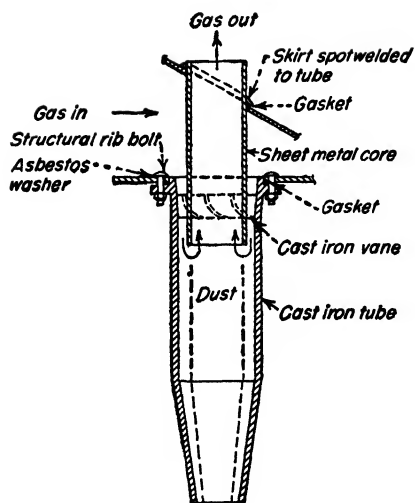


FIG. 14-10

FIGS. 14-9 and 14-10. General arrangement of Multiclone collector; lower cut shows operation of single cone. (Western Precipitation Co., Los Angeles.)

through a small collector for precipitation into a suitable container, the secondary air or gas being returned to the inlet of the cone, where it again passes through the same

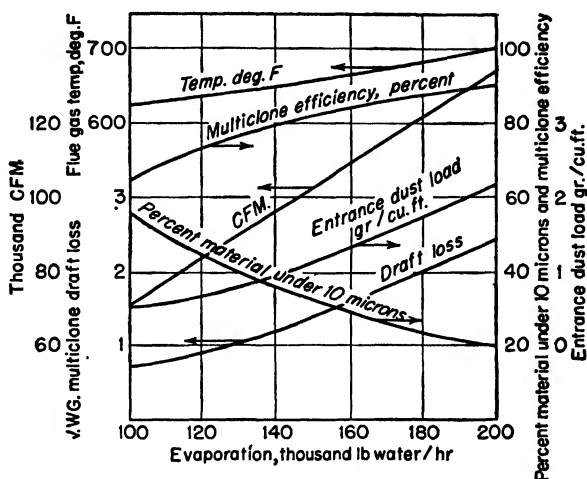


FIG. 14-11. Relations between operating conditions and Multiclone characteristics. ("Fly Ash Elimination," Western Precipitation Corp., Los Angeles, p. 19, 1946.)

process. There are over 800 installations of this type in Sweden, where the apparatus is known as "Bahco."

**Multiclone Separators.** Cyclones are most effective when called upon to remove the coarser and heavier particles. Their effectiveness varies directly as the square of the entering velocity and inversely as the diameter of the cyclone. Hence a series of small cyclones will remove more and finer dusts than a single large unit. This has led to the development of cyclone dust collectors with a large number of elements of small diameter. These may be highly effective for removing particles of both large and medium diameters.

Such devices require a relatively high pressure drop (to 3 in. water and even higher), which increases both installed and operating expense as they must almost invariably be installed in conjunction with induced-draft equipment.

According to the Western Precipitation Corp. (Los Angeles), the collection efficiency of a Multiclone dust (trade name) collector as operated on different materials is as shown in Table 14-13.

**Operating Conditions vs. Collection Efficiency.** It will be noted from Fig. 14-11 that gas volume increases almost directly with boiler steaming rate. As the draft loss

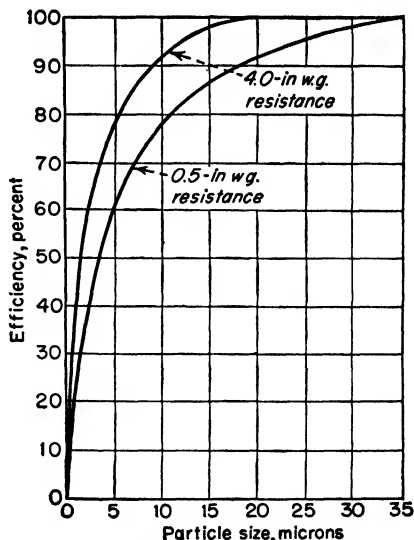


FIG. 14-12. Effect of flow resistance on tube efficiency. (For Aerotec tube, Design 3 the Aerotec Corporation, Greenwich, Conn. Temp, 400°F; specific gravity, 2 to 2.2.)

through any mechanical collector varies as the square of the volume passing through the collector, this draft loss increases rapidly with the increase in steaming rate.

The percentage of coarse material from stoker-fired boilers is much greater at high steaming rates, because of the greater carrying power of the high-velocity gas. Therefore, as mechanical collector efficiency increases rapidly with increase in particle size, the percentage collection efficiency is highest at high steaming rates. To offset this, however, the total amount of fly ash at low steaming rates is very much smaller, so that high efficiency at low steaming rates is of very little consequence. Thus it will be seen that the characteristic desired in collection equipment is the highest practical collection efficiency at normal load compatible with maximum permissible draft loss at peak loads.

Table 14-14. Performance of Centrifugal Dust Collector with Testing Sample<sup>1</sup>

Particle size, microns	Per cent of sample by weight	Avg size, microns	Collector efficiency, per cent	Per cent collected by weight	Relative weight	No. of particles/cu ft	No. of particles collected/cu ft
+420	7 7	420	100 0	7 7	72,000,000	9	9
175-420	33 6	298	100 0	33 6	26,300,000	107	107
150-175	9 9	163	100 0	9 9	4,300,000	192	192
75-150	22 1	113	100 0	22 1	1,440,000	1,280	1,280
40-75	19 0	58	100 0	19 0	194,000	8,200	8,200
30-40	3 7	35	100 0	3 7	42,900	7,200	7,200
20-30	1 7	25	100 0	1 7	15,600	9,100	9,100
15-20	0 8	17 5	98 0	0 79	5,360	12,400	12,200
10-15	0 4	12 5	95 0	0 38	1,950	17,100	16,200
7 5-10	0 35	8 75	90 5	0 31	670	43,500	39,400
5-7 5	0 25	6 25	85 0	0 21	244	84,000	71,300
4-5	0 17	4 50	78 0	0 13	91	156,000	122,000
1-4	0 18	2 50	63 5	0 12	15 6	960,000	610,000
0-1	0 15	0 50	30 0	0 05	0 1	100,000,000	30,000,000
Totals	100 00			99 69		101,249,088	30,000,000

<sup>1</sup> *The Project Engineer*, The Thermix Co., Greenwich, Conn., vol. 6, No. 2, p. 4.

### Electrical Precipitators

All electrical precipitators follow the same general principle in that a corona discharge is set up. This is usually of 30,000, 60,000, 75,000, or 90,000 volts, with the 60,000- and 75,000-volt potentials being the most common for large industrial precipitators. This potential imparts a negative charge to the gas-borne dust particles so that they may become attracted to the positive poles of the precipitator to which they may adhere. In dry-collection-type precipitators the material is usually mechanically dislodged from the collecting electrodes, such as by rapping, for collection in hoppers.

The **high-voltage electrodes**, necessarily supported from high-voltage insulators, must either be small or have sharp edges to facilitate the formation of corona. Two typical forms are (1) 10-gauge steel wire and (2)  $\frac{1}{8}$ ,  $\frac{3}{16}$ , or  $\frac{1}{4}$ -in. twisted square steel rods.

**Collecting electrodes** must have maximum collecting surface, must be structurally stable, must vibrate in unison with the rapper for maximum effectiveness of cleaning, and must hold the trapped dust as well as possible. Their design has a great deal to do with the ultimate efficiency of the precipitators.

Both vertical and horizontal gas-flow precipitators are available in many forms, including the following, classified by type of collecting electrodes: (1) rod curtains, consisting of many small-diameter pipes hung vertically in horizontal-flow precipitator; (2) corrugated plate, with curtain collecting electrodes for either horizontal or

vertical types; (3) graded resistance, with curtains of cast concrete with entrained rods (are heavy, must have scrapers instead of rappers, and tend to spall) (4) dual plates; (5) pocket electrodes of V-shaped strips hung vertically with the apex of the V facing the gas stream; and (6) high-duty type, with specially bent steel strips forming a dust spout between two sides of the electrode, vertical flow.

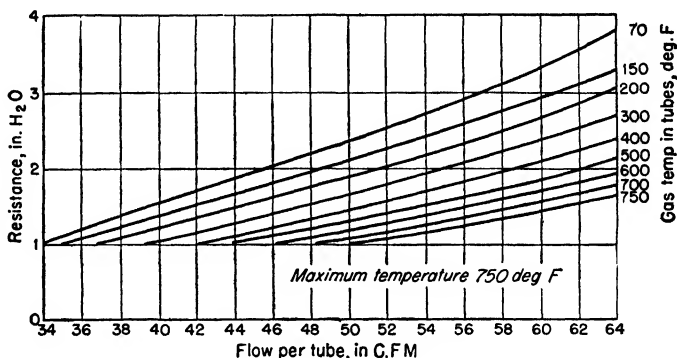


FIG. 14-13. Aerotec tubes. Relation between flow per tube and resistance for various temperatures. NOTE: For higher resistance, volume increases as the square root of resistance.

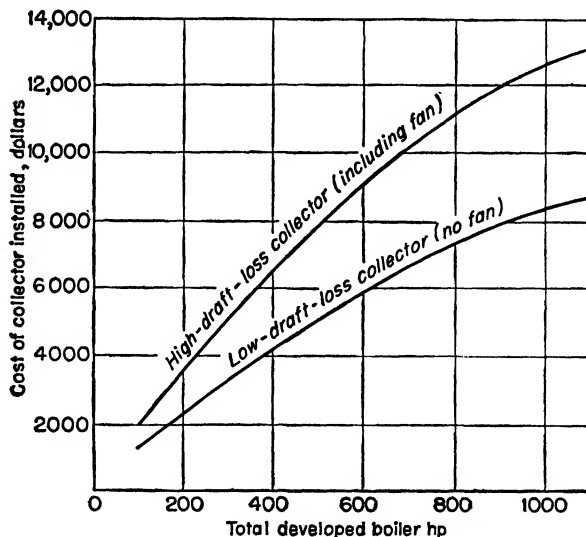


FIG. 14-14. Estimating prices for small fly-ash collectors. (Miller, Carl T., "What Can the Small Plant Do About Fly Ash," Bituminous Coal Research, Inc., 1949.)

The proper removal of the dust from the electrodes without redepositing it in the gas stream is a most important phase of design and varies widely for the different types of dust. In general, properly timed light blows of a rapper accomplish this most effectively.

**Applications.** While electrical precipitators can be built to collect dust in almost any particle size, they will not collect material in the gaseous or vapor stages; these must be condensed for electrical precipitation.

Dry-type precipitators can handle inlet dust loadings up to about 25 grains per cu. ft. of gas. With greater dust concentrations, mechanical separation to remove the coarser fractions is advisable.

Where the dust has high electrical conductivity, as with carbon, difficulty is sometimes encountered because the captured particles lose their charge rapidly upon contacting the collecting electrode and reentering the gas stream. This process may be repeated through several cycles before the precipitator exit is reached. For this and other special conditions, combination methods are sometimes used for recovery.

**Precipitator Sizes.** Western Precipitation Corp., Los Angeles, manufacturers of the Cottrell electrical precipitator, lists rectifiers in the following sizes: 2½, 5, 10, 15, and 25 kva.

**Efficiency of Precipitation.** The efficiency of a precipitator is expressed by the equation

$$\log (1 - E) = t \log K^0$$

where  $E$  is the precipitator efficiency expressed decimally,  $t$  the time in seconds that the gas remains in the active field of the precipitator, and  $K$  a constant for the particular precipitator and dispersoid. The constant  $K$  is always less than 1 and may vary from 0.05 to 0.80. Since the efficiency varies logarithmically, it can be seen that the size of a precipitator increases exponentially with increase in required efficiency. Likewise the cost of a precipitator increases in greater than a straight-line proportion to the increase in required efficiency.

In general, the efficiency of electrical precipitation may be expected to be between 90 and 95 per cent.

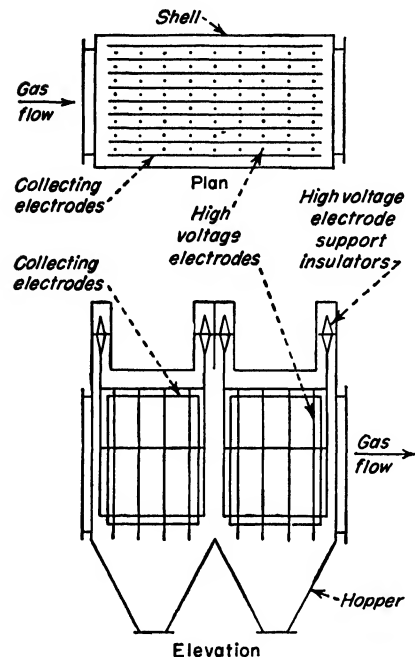


FIG. 14-15. General scheme of Cottrell electrical precipitator. (Western Precipitation Corp., Los Angeles.)

Conditioning the gas is very important for maximum efficiency with electrical precipitators to eliminate the collection of ionized gas between collected dry dust particles which lowers the spatial resistance. Conditioning agents introduced into the entering gas stream, such as steam, water, triethylamine, salt solution, ammonia, and other conductive and wetting agents, overcome this difficulty. They, in turn, must be carefully controlled to prevent muddying the precipitator.

### Sonic Precipitation of Fine Particles<sup>1</sup>

Sound waves of high intensity are now being used successfully in commercial fine dust- and mist-collection systems. Such a system consists of an agglomeration tower containing the sonic generator, followed by cyclone separators. In such collectors, fine solid or liquid particles, particularly those smaller than 10 microns in diameter, may be agglomerated into larger clusters, heavy enough to be readily collected by cyclone separators. Such fine particles, unagglomerated, are so light that they tend

<sup>1</sup> DANNER, HAROLD W., President Ultrasonic Corp., Cambridge, Mass., "Status of the Development of Industrial Sonic Agglomeration and Collection Systems," ACS Technical Paper, San Francisco, 1949.

to remain air-borne and to pass directly through a cyclone. The high-intensity sound waves effect agglomeration by causing the smaller particles in a gas stream to vibrate wildly while the larger particles, being heavier, are less agitated. Collision expectancy is thereby sharply increased. The small particles collide with, and adhere to, the larger particles. Aggregates, frequently composed of hundreds of small particles, are rapidly built up and may then be collected by cyclones easily.

**Sizes of Sonic Generators Available.** Ultrasonic Corp. manufactures siren-type generators in two sizes: Model U-4 for pilot-plant and small commercial gas streams of up to 3,000 cfm and Model U-3 for gas streams up to 50,000 cfm. Multiple installations of such collectors are also feasible.

Intensity of the sound wave is governed by the pressure of the compressed air, frequency by the speed with which the rotor is driven. (A General Radio Co. "Variac" speed control in the motor circuit is recommended for adjustment of the motor speed and frequency.)

Model U-4, for processing air streams up to 3,000 cfm, has an adjustable frequency range from 500 to 22,000 cycles per sec. With 7 psig at the generator, approximately 230 cfm of compressed air or gas is required, indicating the need for a 10-hp compressor, in addition to a 12,500 rpm  $1\frac{1}{2}$  hp explosionproof generator-drive motor.

Model U-4, processing up to 1,500 cfm, operates with 5 lb air pressure, requiring 150 cu ft of free air delivery. At this air pressure, the generator acoustic output is about 300 watts in the range from 1 to 5 kc, this output decreasing to an indicated 200 watts at the maximum frequency of 22 kc. Sound pressure level increases from 150 to 165 db above 0.0002 dynes per sq cm measured in a free field. The motor drive requires from 100 to 650 watts in the 1- to 10-kc spectrum and then up to 2,300 watts at 22 kc. The compressor for 5 psi operation will require about a 5-hp motor.

**Factors in Agglomeration.** There are three principal variables in the agglomeration of aerosols<sup>1</sup> in large gas volumes (5,000 to 50,000 cfm), viz., (1) the intensity of the sound field in which the aerosol is treated, (2) the exposure time in this field, and (3) the frequency of the sound.

**Intensity of Sound.** The intensity or sound-pressure level in an acoustic field is usually measured in decibels (db) above  $10^{-16}$  watts per sq cm. The threshold value causing noticeable agglomeration in a reasonable time is approximately 140 db. However, for effective industrial practice, something upward of 150 db appears to be required. In a properly designed installation, from 40 to 60 per cent of the energy in the compressed gas may be converted into sound.

**Exposure Time.** Since the process of agglomeration depends upon collision between the particles involved, it follows that as exposure time is increased a larger number of collisions will ensue. However, there appears to be an upper limit beyond which an increase in exposure time will not significantly improve the degree of agglomeration. For a given exposure time and field intensity, this limit will obtain when agglomeration has proceeded to the point where the particles become few in number compared with the volume they occupy. In general, given a sufficiently intense acoustic field of proper frequency, exposure time may be on the order of only a few seconds (say, up to about 4 sec).

**Frequency of the Sound.** For work upon an aerosol having a given particle size, there will be a range of favorable frequency of operation. There will be a frequency at which great relative motion is caused by the different-sized particles, resulting in a maximum number of collisions. Experience indicates that this best frequency may extend down to the order of 1.0 kc for particles of 10 microns in size, and somewhat higher for particles of, say, 0.01 microns. Generator efficiency and treating-chamber effectiveness are also functions of frequency.

<sup>1</sup> Aerosols, a suspension of fine solid or liquid particles in air or gas as smoke, fog, or mist.

**Applications of Sonic Collectors.** *Evaluation of Fields of Use.* Sonic collectors are applicable to the recovery of a gas of particles smaller in size than those readily collected by conventional cyclone separators (say, less than 10 microns). Such particles are so light that they tend to remain air-borne and to pass directly through a cyclone. Below 1 micron, sonic treatment may be effectively used to so agglomerate them as to permit their cyclonic separation. There appears to be no lower limit of particle size in a visible fume or dust below which sonic agglomeration becomes ineffective.

**Temperature,** within reasonable limits, does not impose restrictions. Thus, gas temperatures may range from below 0°F to above 1000°F without impairing efficiency of sonic agglomeration. At extreme temperatures, of course, special consideration must be given to the materials of construction.

Sonic agglomeration seems independent of the **electrical characteristics** of the particles. Thus, inert particles and those characterized as insulators may be effectively collected.

There is a complete absence of fire hazard. The gas passed through the sound generator may be air, steam, or an inert gas, or even the process gas itself.

There must be a sufficient **number of particles** in each cubic foot of gas so that, as the particles are vibrated in the acoustic field, there may result the proper number of collisions between the particles. If the particles are too widely separated, an adequate degree of agglomeration may not be achieved. The required particle weight per cubic foot will vary inversely with the average particle size. As a rough approximation, 1 grain per cu ft is sufficient when the particle sizes range from 1 to 10 microns, but the grain-loading figure may decrease somewhat for aerosols in which the average particle is smaller than 1 micron, since a larger number of collision targets is available. When the normal grain loading is too small, such techniques may be employed to increase it as spraying or condensing water or other liquid into the aerosol, mingling a second aerosol with the first, and increasing the loading by cooling to reduce the volume.

**Applications.** In addition to alleviating such nuisance problems as smoke, obnoxious fumes, dust, and smog, there is a broad field of recovery of materials where sonic collection might be advantageously applied. These include the recovery of materials through the petroleum, smelting, chemical, steel, carbon black, cement, lime and rock products, sulphur, paper, and other process industries.

**Cost of Sonic Collection.** According to Ultrasonic Corp., the installed cost of industrial-scale sonic collection systems range down to below \$1 per cubic foot of installed capacity. They further state that over-all operating cost, including power plus operating and maintenance labor, ranges down to below 0.7 mil per thousand cu ft of gas treated.

**Examples of Sonic Application.** The Ultrasonic Corp. has an experimental installation at a plant of the Chemical Construction Corp. of New York. This installation is for the collection of sulphuric acid fog from exit stack gases of a contact-type sulphuric acid plant. The exit stack gases leaving the absorption tower enter a humidification chamber, where  $\text{SO}_3$ , passing through water sprays, is converted to  $\text{H}_2\text{SO}_4$  mist, whose particles range from 0.5 to 5.0 microns in diameter. The gas stream contains 24,000 cfm at 125°F. It is introduced tangentially into the bottom of a cylindrical agglomeration tower 8 ft in diameter and 35 ft high where it is treated and subsequently passed through cyclones to the atmosphere. When the sound generator is not operating, the acid fog particles pass vertically through the tower, entirely through the cyclones, and into the atmosphere. With the sound generator operating, however, a sound pressure field of over 150 db is produced throughout the tower. Initial operations show that, with less than 4 sec exposure, the fine particles are agglom-

erated to such a size that over 90 per cent by weight of the acid may be removed from the gas stream; about half in the inner walls of the tower, the remainder within the cyclones.

A second example is that of the Ultrasonic Corp. in conjunction with Combustion Engineering-Superheater, Inc., of New York. This installation is for the collection of soda-ash fumes from the stack gases leaving a recovery boiler in a paper mill. The arrangement of parts is similar to that of the first example. Gas flow rate measures about 50,000 cfm at 200°F. The fume particles average less than 1 micron. Exposure to the sound field is less than 4 sec. In such an installation, the value of the recovered material can be applied against amortization of the equipment cost.

### Combinations of Collectors

**Use of Combination Collectors.** In some instances, a combination of an electrical precipitator and mechanical collector can be used effectively. For example, combinations of the Multiclone and Cottrell systems have been used for collecting fly ash from pulverized-coal-fired boilers and for the selective collection of materials from cement kilns.

In a typical operation on a boiler, the Multiclone effectively collects the larger sized fly-ash particles and a smaller precipitator collects the smaller sized material missed by the mechanical collector. The combination thus results in satisfactory over-all collection at less cost than straight precipitation.

Christie<sup>1</sup> also points to certain potential advantages of locating the precipitator ahead of the collector, such as its ability to pick up material lost by rapping when in this position.

Where dust loads are heavy and there is a reasonable percentage of +10-micron material in the dust, it may be advisable to consider a combination unit. In general, when the dust loading exceeds 25 grains per cu ft of gas, the precipitator must be so efficient to do a satisfactory cleaning job that a combination should be considered.

**Combination Efficiency.** In considering collector-precipitator combination efficiency or effectiveness, it should be noted that it is the material escaping that is of interest and not the material held. Thus, if two collectors, each with an efficiency of 90 per cent, are used in combination, their total or combined efficiency would be 99 per cent. This is by reason of the fact that the second would extract 90 per cent of the 10 per cent left from the first, to leave only 1 per cent for the exhaust.

**Ultimate Collection and Disposal of Dusts.** Dry flue dusts are usually removed from hoppers by screw conveyors or other means of ejection. They must be thoroughly wetted before placement, usually by mixing with water in a pugmill. Their disposal is a serious problem that has not as yet been solved with any real degree of satisfaction. About the only current use is as a fill for low areas, and even here they are likely to be carried back into the air by winds or to be washed into streams with resultant pollution.

### COMMERCIAL POTENTIALITIES OF SOLID-FUEL REFUSE

Numerous attempts have been made to convert ash, clinker, and fly ash from coal and coke into an asset through finding commercial uses for these by-products of combustion.

**Cinder Concrete.** Aside from the familiar use of cinders, and, to a lesser extent, ash as a medium for fill, undercourses in paving, etc., the most extensive use for solid-fuel refuse is as a raw material for cinder concrete. For example, it has been estimated that over 500 million cinder brick are used per year.

<sup>1</sup> *Loc. cit.*



Christensen,<sup>1</sup> representing the American Concrete Institute, has proposed the following specifications for cinders for sand-cinder concrete:

Cinders, when used for concrete, shall be the product of high-temperature combustion of coal and/or coke—known as “industrial cinders,” “boiler cinders,” or “steam cinders,” to the exclusion of the residue from domestic furnaces. The cinders shall be well burned, free from foreign matter, and so graded from coarse to fine as to produce a cinder concrete (or sand-cinder concrete) meeting the strength requirements of the building code. The cinders shall contain not more than 35 per cent of combustible content by weight, nor more than 0.45 per cent sulphur as sulphide, nor more than 1.00 per cent sulphur trioxide as sulphate.

**Soil-lightening Medium.** Light ashes, particularly those from domestic anthracite and coke, have been used for some time as a medium to break up heavy soils. The 1938 “Agricultural Yearbook”<sup>2</sup> says:

While possessing practically no fertilizing value, coal ashes, when properly sifted and incorporated with heavy soils (clays and clay loams in particular), exert a beneficial effect on physical condition through improvement of tilth and drainage. Indirectly, therefore, coal ashes may prove worth while in the amelioration of heavy soils around the home grounds and in small gardens.

A 2-in. layer of ashes, well worked into the topsoil, is usually a correct amount, with as much as 25 per cent ash being needed for the proper conditioning of very heavy soils.

**Mineral Wool from Refuse.** Rose and Johnson<sup>3</sup> proposed the use of anthracite-colliery refuse and anthracite ashes as a raw material in the manufacture of mineral wool, and described tests conducted to prove the feasibility. A good-quality white mineral wool was produced. Lack of acceptance commercially would seem to indicate that manufacturers find the collection and preparation of ash less advantageous economically or otherwise than the retention of their present sources of raw materials.

**Lightweight Aggregate.** The use of cinder ash for the production of lightweight concrete has been extensive. In one instance, a lightweight tongue-and-grooved concrete plank for roofs and floors, sold under the name of *Cantilite*, was approved by the City of New York Board of Standards and Appeals. Their approval required that the planks be made of cement and anthracite cinders.

**Lelite.** While strictly speaking not a product of ash or other refuse from combustion, since it is made from the sintering of a carbonaceous shale refuse from the mining operations with anthracite, Lelite is nevertheless a by-product of the coal industry. It is a lightweight aggregate, structurally strong, chemically inert, cellular, and vitreous. It is marketed in two sizes: No. 8 sand which consists of No. 8 Tyler screen and smaller; and,  $\frac{3}{4}$ -in. size which has a sizing between  $\frac{3}{4}$  in. and No. 8 mesh. Properties claimed are: strength of concrete, 4,000 psi or even more; insulating properties; fire-resistant, because of its having been sintered at 2800°F; and chemical inertness. Concrete made with Lelite will weigh from 90 to 100 lb per cu ft air-dried. Lelite is made by Lelite Materials Co., a wholly owned subsidiary of Lehigh Navigation Coal Co., both of Lansford, Pa.

**Commercial Potentialities of Fly Ash.** C. M. Weinheimer<sup>4</sup> lists the commercial potentialities of fly ash as follows:

1. There are only a few industries that can use the quantity of ash produced by a large steain plant.

<sup>1</sup> CHRISTENSEN, E., Cinders as Concrete Aggregate, *J. Am. Concrete Inst.*, vol. II, February, 1931. Also available from American Concrete Institute as a reprint.

<sup>2</sup> SCHRIENER, O., A. R. MERZ, and B. E. BROWN, Fertilizer Materials, “Yearbook of Agriculture,” p. 516, U.S. Department of Agriculture, 1938.

<sup>3</sup> ROSE, H. J., and R. C. JOHNSON, Mineral Wool from Anthracite Colliery Refuse and Anthracite Ashes, *Trans. 3d Ann. Anthracite Conf. Lehigh Univ.*, p. 45, 1940.

<sup>4</sup> WEINHEIMER, C. M., Evaluating the Importance of the Physical and Chemical Properties of Fly Ash in Creating Commercial Outlets for the Material, *Trans. ASME*, vol. 66, p. 551, August, 1944.

Table 14-15. Industrial Survey of Fly-ash Disposal<sup>1</sup>

Industry	Material previously used	Can ash be used		Remarks
		Technically	Com- mercially	
Acoustic, dum dum .....	Slag dust	Questionable	Yes	Too light in weight
Agriculture:				
Fertilizer.....	Spent sand	No	No	Too fine; spent foundry sand delivered for \$0 40 per ton
Soil-amendment agent	Unknown	Yes	Yes	Probably would not produce any revenue
Alumina . . . . .	Bauxite	Yes	No	Uneconomic under present conditions
Building block:				
Cement block ...	Cement	Yes	No	Detroit market demands light-colored block
Cinder block . .		Yes	Yes	Improved quality of block
Cottrell block ...		Yes	Yes	
Glazed block		Yes	Yes	Glazed, colored tile for decorative work
Building brick:				
Fired . . . . .	Clay	No	No	Unsatisfactory product
Sand lime . . .	Sand	No	No	Unsatisfactory product, dark color
Ceramic industry:				
Drain tile . . .	Clay	Yes	No	No improvement in quality of product and cost of manufacture increased
Hollow tile . . .	Clay	Yes	No	
Flowerpots . . .	Clay	Yes	No	
Concrete:				
Transit mixed .....	Cement	Yes	Yes	Improves quality, reduces cost
Cinder ash .....		Yes	Yes	Lightweight concrete
Floor tile, asphalt tile....	Clay	Yes	No	Shipping distance too far. Color limitation
Foundry:				
Core sand . . . . .	Sand	No	No	Too fine; makes a dense core
Parting sand . . . .	Limestone dust	Yes	Yes	Aluminum and magnesium foundries
Facing sand . . . .	Sand	No	Yes	Softening point too low for steel
Hot tops . . . . .	Calced clay	Unknown	No	Believed to be unsatisfactory
Gaskets . . . . .	Clay	Unknown	Yes	Believed to be unsatisfactory
Paint.....	Extender	Questionable	Yes	Lacks covering power; difficult to disperse
Paper. ....	Clay	No	Yes	Color, no matting properties
Plastics. . . . .	Diatomaceous earth	Questionable	Yes	Poor quality of product
Polishing:				
Buffing compound ..	Pumice	No	Yes	Does not produce desired finish
Tooth paste	Whiting	No	Yes	Too hard
Portland cement, raw material. ....	Clay	Questionable	Yes	High alumina content is objectionable
Purification:				
Water filter. . . . .	Sand	Questionable	....	Market small; properly graded material required
Oil	Fuller's earth	No	Yes	Does not produce clarification
Filter aid . . . . .	Diatomaceous earth	No	....	Does not function as such; wrong type of particle
Zeolite . . . . .	Zeolites	Yes	No	Small fraction satisfactory; low capacity
Putty:				
Furnace cement	Whiting		...	No information was obtainable
Sash putty	Whiting	Questionable	..	Dark color objectionable
Caulking compound .	Asbestos	Questionable	..	Dark color objectionable
Road:				
Asphalt	Limestone	Yes	Yes	Lower cost
Concrete	Cement	Yes	Yes	Lower cost; improved product
Oil aggregate. . . .	Limestone	Yes	Yes	Lower cost
Roofing . . . . .	Filler	Unknown	No	No market
Roofing	Slate granules	No	Yes	Too fine
Rubber	Clay	Questionable	Yes	Seems to have possibilities
Soap, mechanic's ....	Pumice	Unknown	Yes	Small market; dark-colored soap
Thermal insulation:				
Insulating cement.....	Calced clay	Yes	Yes	Improved product
Loose fill.....	Mineral wool or vermiculite	Yes	No	Can be used only in the cells of masonry building blocks

<sup>1</sup> WEINHEIMER, C. M., Physical and Chemical Properties of Fly Ash, *Trans. ASME*, vol. 66, p. 555, 1944.

2. The ceramic industry, which is a large consumer of clays, is not likely to become a user of fly ash because of the cheapness with which clays are delivered to the ceramics plants and because the ash does not generally have the proper properties to improve the quality of the product.

3. Certain types of fly ash are satisfactory as mineral fillers in bitumastic road construction.

4. Certain types of fly ash improve the quality of standard concrete, make possible a new lightweight concrete, and also open the way to a possible reduction in the cost of concrete.

5. The seasonal load factor of the mineral filler and the concrete markets makes it desirable to develop a year-round outlet of large tonnage, such as in the fields of rubber or plastic filler.

6. Regardless of the merits of fly ash as a material, it cannot be sold commercially unless the customer's handling problem is satisfactorily solved.

7. There will be no fly-ash disposal problem if the sales resistance of the concrete industry and the bitumastic-road industry can be overcome.

### EXTERNAL DEPOSITS ON BOILER HEATING SURFACES<sup>1</sup>

The British Boiler Availability Committee has made a very careful study of the external deposits on various boiler heating surfaces. Those found in the furnace, on the superheater, and in the boiler proper have been classified as high-temperature deposits, while those occurring on economizer surfaces and air heaters are termed low-temperature deposits.

#### High-temperature Deposits

In the high-temperature region of stoker-fired boilers, three main types of relatively hard deposits have been identified, *viz.*, (1) **birdnesting**, (2) **bonded deposits**, and (3) **phosphatic deposits**.

**Birdnesting** is generally found on the first bank of boiler tubes, although it is occasionally encountered in high-temperature superheaters. It is more prevalent in older boilers in which the first bank of tubes is set relatively low over the fire or in cases where high superheat requires high furnace outlet temperature. It is often encountered with pulverized coal.

The composition of birdnesting deposits is usually similar to coal ash; *i.e.*, it consists largely of fly-ash particles bound together as the result of sintering. Deposits of the birdnesting type are produced by the sintering or fusion of fly-ash particles which have been sticky and adherent at the prevailing temperatures.

**Bonded deposits** are characterized by the bonding together of ash particles by some sort of cementing substance that softens at relatively low temperatures. They are extremely hard and compact and occur generally on superheater tubes, although sometimes also on boiler tubes. In the opinion of the committee, they are the most serious with regard to boiler availability.

Such deposits differ from those in birdnesting in that they contain from 10 to 50 per cent of material that is soluble in water, the soluble portion being composed chiefly of sulphates or bisulphates of sodium and potassium which provide the bonding. The bisulphates are more troublesome than the sulphates, partly because they melt at lower temperatures and partly because they combine with certain kinds of fly ash

<sup>1</sup> Digest of Interim Report of British Boiler Availability Committee, *Combustion*, March, 1947, p. 26. WALSE, E. F., Protective Coating Prevents Slag on Boiler Heating Surfaces, *Power Generation*, Chicago, July, 1949, pp. 74-75. Pertinent additional references include: JOHNSTONE, H. F., Corrosion of Power Plant Equipment by Flue Gases, *Univ. Illinois Eng. Expt. Sta. Bull.* 228. YEAW, JESSE S., and LOUIS SINDMAN, Dew Point of Fuels containing Sulphur, *Power Plant Eng.*, January, February, March, 1943. HARLOW, W. F., Causes of High Dew Point Temperatures in Boiler Flue Gases, *Engineering*, 1943. WALSE, E. F., "Some Aspects of the Cause and Prevention of Slag Deposits on the Heating Surface of Modern High Pressure Boilers," ASME, spring meeting paper, New London, Conn., May, 1949.

(that formed from pyrites in the coal) to form slaglike aggregates. A number of tests revealed that the flue gas in the regions where bonded deposits existed was hot enough to cause sintering of the cementing material but not hot enough to soften the fly ash. Furthermore, it was observed that the inner layers of the bonded deposits were generally lighter in color than the outer layers. This was attributed to the fact that the inner layers contain a larger proportion of sodium and potassium salts, whereas the outer layers are almost wholly fly ash.

**Phosphatic deposits** are similar in appearance to the bonded deposits, but they are bound together as a result of the chemical attack of the fly ash. This attack is made by phosphorus compounds volatilized from the burning fuel. Difficulties from this type of deposit were not numerous, however, since only a small proportion of the coals encountered contained phosphorus in sufficient quantity to cause such deposits.

### Low-temperature Deposits and Corrosion

Deposits formed on the heating surfaces of economizers are generally harder and more compact the higher the feed-water temperature. They are composed of fly ash and condensed substances, together with the products of complex chemical reactions. Moreover, the nature of the coal burned seems to have greater effect on the composition of economizer deposits than it has on the fly-ash type of high-temperature deposits. This is especially true where phosphorus is concerned, its compounds often having a bonding action on low-temperature deposits. Even the amount of phosphorus released from the coal may not be high enough to cause trouble in the high-temperature region.

Economizer deposits range in composition from some that are rich in sulphate but contain little phosphate to others that contain a larger proportion of phosphates and less sulphate. In general, the richer the deposit in phosphate the less soluble it is, and the greater will be the difficulty in its removal.

All troublesome air-heater deposits are characterized by the presence of free sulphuric acid. They tend toward a grayish color which is determined partly by the amount of unburned carbon present and partly by the size of the fly-ash particles.

While corrosion in air heaters often results when the temperature in the coldest section falls below the dew point of the gases, it may also occur at higher metal temperatures when small quantities of sulphuric acid raise the dew point of the gas to 300°F or more.

**Composition of Deposits.** A significant point resulting from an analysis of many of the deposits is that certain of their constituents are present in far greater proportions than they are to be found in the coal ash. The most striking example of this concentration of material is shown by phosphorus. The same trends are shown by sodium and potassium and to a lesser degree by sulphur. The various materials seemed to be formed from substances volatilized from the burning fuel.

A typical example of selective deposition is the high-temperature deposit bonded by a matrix of sodium and potassium sulphates. It has been found that the softening temperature of the matrix and the sintering temperature of the deposit generally lie between the actual temperature of the heating surface and the gas temperature in the vicinity. It is believed that selective deposition caused by the gas and heating surface temperatures may account not only for the production of deposits rich in sodium and potassium on boiler tubes, but also for the presence of large proportions of other substances in other sections, such as the economizer.

A study of the volatilization of various materials from the fuel bed showed that the sodium and potassium are easily driven off and appear to come principally from areas of the fuel bed where the temperature is high and where smoke is absent. While most of the sulphur in the gas appears as sulphur dioxide, some of the latter is oxidized as

sulphur trioxide, although sulphur trioxide may also be released directly from the fuel bed by decomposition of substances such as calcium sulphate. It is believed that the sulphur trioxide is not only responsible for air-heater corrosion but also plays an important part in the formation of high-temperature deposits.

Evolution of phosphorus has been found appreciable only when there are chemical reducing conditions in the fuel bed, and when temperatures are sufficiently high.

Various chemical changes appear to take place in the vapor phase before the constituents concerned are finally deposited as sulphates, bisulphates, phosphates, or sulphuric acid. The study of such changes, particularly the mechanism by which the sodium and potassium combine with sulphur and with oxygen to form the bonding material of high-temperature deposits, suggests that the process involves reaction of the sodium and potassium vapors with sodium trioxide. Subsequently the sulphates or bisulphates are deposited on the boiler heating surfaces where they produce the white inner layer of the material that is so characteristic of such deposits. This layer, which contains little ash and a large proportion of material soluble in water, provides a foundation for the deposition of additional solid or semisolid particles.

#### Catalytic Action by Rust

Investigation has shown that sulphur trioxide may also be formed by catalytic oxidation of sulphur dioxide on the boiler surfaces, particularly on the superheater where it is at the necessary temperature. Results which have been published indicate that the rust on superheater tubes, and to a lesser extent, deposits on them, are catalytic at the temperatures encountered in modern boilers.

Another fact that seems to be well established is that there is less trouble with high-temperature deposits when there is adequate turbulence of the combustion gases in the furnace.

It has been proved that boilers burning coal containing much chlorine suffered severely from high-temperature deposits; also, that deposit trouble and particularly air-heater corrosion was bad when coals of high sulphur content were burned.

In examining deposits from plants that burn only coals rich in phosphorus, but low in sulphur and chlorine, it was concluded that such coals can best be burned in pulverized form, and with good availability in traveling-grate stokers, but that rapid development of phosphatic deposits may be incurred if they are burned on retort stokers. This was explained by the fact that the amount of phosphorus available for the formation of deposits seems to be related to the temperature of the fuel bed and to the reducing or oxidizing conditions that exist, and combustion on retort stokers is under relatively reducing conditions. It was suggested that similar trouble might arise on traveling-grate stokers if too deep a fuel bed were carried or if the air supply was not uniform. (Experience with anthracite has indicated that dirty or contaminated coal, such as yard screenings, is apt to cause the formation of deposits, as is poorly sized coal.) All flue dusts examined from pulverized-coal-fired boilers contained very little phosphorus. Coals of medium phosphorus content (about 0.02 per cent) were not found to be associated with troublesome phosphatic deposits.

#### Protective Coating to Prevent Slagging<sup>1</sup>

Rylands and Jenkinson<sup>2</sup> observed a period of "immunity" with new boiler installations of from 6 to 12 months. During this time, a film of scale is assumed to build up slowly on the surface of the metal, after which the action is very much accelerated. Various investigators have found this film to be ferric sulphate or ferric oxide. As

<sup>1</sup> WALSH, E. F., *Protective Coating Prevents Slag on Boiler Heating Surfaces, Power Generation*, Chicago, July, 1949, pp. 74-75.

<sup>2</sup> RYLANDS, J. R., and J. R. JENKINSON, *Bonded Deposits on Economizer Heating Surfaces, Engineering*, 1943.

this is a powerful catalyst in the oxidation of  $\text{SO}_2$  to  $\text{SO}_3$ , the production of sulphuric acid becomes much more accelerated from this time on.

Recognizing the importance of this period of initial immunity, Walsh coated the gas surfaces of two boilers with lime slurry and secured entirely effective results.

Walsh first neutralized the metal surfaces before applying the lime by an 8-hr spray with soft water from a hot-process softener, having a pH value of not less than 11 and a  $\text{PO}_4$  content of not less than 10 ppm. The slag absorbed sufficient water to dissolve the binder between the metal surfaces and the slag, making it easily removable. After all the slag was removed, the metal surfaces were washed with alkaline water until the acid in the pores of the metal was completely neutralized. The same treatment was given to the induced-draft fans, air preheaters, and duct work. A lime slurry was then prepared by dissolving hydrated lime in water to a consistency that could be sprayed with a commercial paint gun. All metal surfaces were thoroughly coated. Walsh reported a year of operation on one boiler and 16 months on another "without any appreciable deposits." The absence of the usual acid paste in the duct work was also noted.



**SECTION 4**

**SELECTION OF A FUEL**





## CHAPTER 15

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### FACTORS INVOLVED IN THE SELECTION AND PURCHASE OF FUEL

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Table 15-1. Direct Heat-value Ratios of Various Fuels<sup>a</sup>

Fuel												
Anthracite	Bituminous	Wood		Coke	Fuel oil			Mfg gas	Natural gas	LPG		Electricity
					No. 1	No. 2	No. 6			Propane-butane		
Units												
Tons	Tons	Tons	Cords	Tons	Gal	Gal	Gal	Cu ft	Cu ft	Lb	Gal	Kwhr
Btu												
26,000,000	28,000,000	18,000,000	21,000,000	25,800,000	137,300	141,800	148,000	525	1,000	21,400	97,000	3,413
1	0.93	1.44	1.24	1.01	188.7	183.4	175.7	49,520	26,000	1,215	268.1	7,618
1.08	1	1.56	1.33	1.09	203.2	197.5	189.2	53,333	28,000	1,308	288.7	6,517
0.69	0.64	1	0.86	0.70	130.6	126.9	121.6	34,290	18,000	841.1	185.6	5,274
0.81	0.75	1.17	1	0.81	152.4	148.1	141.9	40,000	21,000	981.3	216.5	6,153
0.99	0.92	1.44	1.23	1	187.2	182.0	174.3	49,140	25,800	1,188	366.0	7,560
0.0053	0.0049	0.0077	0.0066	0.0053	1	0.968	0.930	262.5	137.3	6.44	1.42	40.2
0.0055	0.0051	0.0079	0.0068	0.0055	1.033	1	0.958	270.1	141.8	6.63	1.46	41.5
0.0057	0.0053	0.0082	0.0071	0.0057	1.07	1.044	1	281.0	148.0	6.92	1.52	43.4
0.000200	0.000188	0.000292	0.000250	0.000207	0.00381	0.00370	0.00355	1	0.525	0.025	0.0054	0.154
0.000384	0.000357	0.000556	0.000476	0.000388	0.00726	0.00700	0.00676	1.91	1	0.047	0.0131	0.293
0.00082	0.00076	0.00119	0.00102	0.00083	0.155	0.151	0.145	40.8	21.4	1	0.221	6.27
0.0037	0.0035	0.0054	0.0046	0.0038	0.704	0.680	0.656	184.8	97.0	4.53	1	28.4
0.00013	0.00012	0.00019	0.00016	0.00013	0.025	0.024	0.023	6.5	3.4	0.16	0.035	1

<sup>a</sup> All comparisons are made on a direct Btu basis without corrections for possible differences in efficiency.

Example. To find the gallons of No. 2 fuel oil equivalent to 1 ton of anthracite, find the 1 in the anthracite column and follow across to the No. 2 oil column, where it will be seen that 183.4 gal is the direct fuel equivalent.

Table 15-2. The Conversion of Various Fuels to Standard Units<sup>1</sup>

<i>Fuel</i>	<i>Units of Standard Fuel per Unit of Indicated Fuel</i>	<i>Fuel</i>	<i>Units of Standard Fuel per Unit of Indicated Fuel</i>
<b>Solid Fuels (by weight):</b>		<b>Liquid Fuels (by weight):</b>	
Coal (standard) . . . . .	1 00	Crude petroleum, shale oil, benzol, and their derivatives (standard) . . .	1 00
German coal . . . . .	0 97	Natural gasoline . . . . .	1 00
German lignite . . . . .	0 31	Motor alcohol . . . . .	0 52
Czechoslovakian lignite . . . . .	0 68	<b>Gaseous Fuels (by volume):</b>	
Other lignite . . . . .	0 387	Gas house gas (standard) . . . . .	1 00
Coal briquettes . . . . .	1 00	Coke-oven gas . . . . .	1 00
Lignite briquettes . . . . .	0 67	Natural gas . . . . .	2 24
Coke . . . . .	0 833	Refinery gas . . . . .	2 91
		Blast-furnace gas . . . . .	0 19

<sup>1</sup> "Energy Resources of the World," p. 124, *U.S. Dept. State Pub. 3248*, June, 1949.

Table 15-3. Assumed Input-Output Relationships for Various Types of Fuel-burning or Processing Plants<sup>1</sup>

Type plant	Input	Output
Briquetting . . . . .	1.00 ton of coal 1.00 ton of lignite	1.063 tons of briquettes 0.355 ton of briquettes
<b>Coke and gas plants:</b>		
Coke ovens . . . . .	1.00 ton of coal	0.74 ton of coke 9,588 cu ft of gas
Gas plants . . . . .	1.00 ton of coal	0.775 ton of coke 15,000 cu ft of gas
<b>Oil and shale plants:</b>		
Oil refineries . . . . .	1.00 bbl of crude	0.80 bbl refined fuels
Shale distilleries . . . . .	1.00 ton oil shale	0.067 ton shale oils
<b>Electric power plants:</b>		
Coal . . . . .	1.00 ton coal	1.52 thousand kwhr
Lignite . . . . .	1.00 ton lignite	0.59 thousand kwhr
Lignite briquette . . . . .	1.00 ton briquettes	1.01 thousand kwhr
Fuel wood . . . . .	1.00 cord wood	0.125 thousand kwhr
Fuel oil . . . . .	1.00 ton fuel oil	2.24 thousand kwhr
Natural gas . . . . .	1.00 thousand cu ft	0.63 thousand kwhr
Manufacturing gas . . . . .	1.00 thousand cu ft	0.28 thousand kwhr

<sup>1</sup> These figures are based on the assumptions used in "Energy Resources of the World," *U.S. Dept. State Pub. 3428*, 1949. They are intended for use in estimating only where more accurate or applicable figures are not available and cannot be obtained.

Table 15-4. Estimated Transportation Cost for Various Fuels<sup>1</sup>  
Petroleum, mils per ton-mile

Tank truck (short haul, less than 100 miles) . . . . .	48 2
Tank truck (long haul, more than 150 miles) . . . . .	15 9
Railway tank car, 724 mils loading cost plus . . . . .	8 6
Pipe line (high estimate) . . . . .	4 76
Pipe line (intermediate estimate) . . . . .	3 18
Pipe line (low estimate) . . . . .	0 84
Tanker (high estimate) . . . . .	1 38
Tanker (low estimate) . . . . .	0 69

## Coal

	Loading, cents/ton	Mils/ton-mile
Rail (hopper car, United States avg) . . . . .	68	7 14
Barge (long haul, Mississippi system) . . . . .	33-35	2 09
Great Lakes vessels . . . . .	50	0 48
Overseas vessels (low rate) . . . . .	50	0 40
Overseas vessels (normal) <sup>2</sup> . . . . .	50	1 00

Electricity,<sup>3</sup> mils per kilowatt-hour

	30 miles	150 miles	300 miles
Load factor, 40 per cent . . . . .	0 85	1 69	2 85
Load factor, 50 per cent . . . . .	0 58	1 18	2 61
Load factor, 60 per cent . . . . .	0 47	1 15	2 37
Load factor 100 per cent. . . . .	0 35	0 77	1 53

<sup>1</sup> "Energy Resources of the World," *U.S. Dept. State Pub. 3428*, June, 1949. All figures shown are based on data or estimates made prior to the Second World War (about 1937) and should thus be revised upward for current use. Except as noted, loading costs are included.

<sup>2</sup> Assuming a "normal" rate of \$7 per ton, Norfolk to Buenos Aires. Overseas costs vary widely with the type of transportation and with the intensity of competition for freight cargoes.

<sup>3</sup> Estimates are based on the delivery of 1 billion kwhr annually and include fixed and operating charges (at 14.5 per cent) and line and substation losses of 2.5, 2.25, 2.10, and 2.0 mils for the 40, 50, 60, and 100 per cent load factors, respectively.

FUEL		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
GUIDE LINES		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NATURAL GAS—1000 BTU per Cu. Ft. Cost per 1000 Cu. Ft.		9	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
CITY GAS—500 BTU per Cu. Ft. Cost per 1000 Cu. Ft.		05	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	100
WATER GAS—800 BTU per Cu. Ft. Cost per 1000 Cu. Ft.		05	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	100
BEST AVAILABLE COAL—100 BTU per Cu. Ft. Cost per 1000 Cu. Ft.		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
PRIME LASH—100 BTU per Cu. Ft. Cost per 1000 Cu. Ft.		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
LINK BREEZE—10,000 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
COKE—12,000 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
COAL—12,500 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
COAL—13,000 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
COAL—13,500 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
COAL—14,000 BTU per Lb. Cost per Net Ton		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
FUEL OIL—140,000 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
FUEL OIL—145,000 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
FUEL OIL—150,000 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
THERMO OIL—150,000 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
BUTANE (Heavy)—102,400 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
BUTANE (Light)—91,800 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
PROPANE (Heavy)—91,800 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
PROPANE (Light)—83,500 BTU per Gall. Cost per Gallon		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ELECTRICITY—3,412 BTU per A.W. Cost per Kilowatt		0004	0006	0010	0015	0020	0025	0030	0035	0040	0045	0050	0055	0060	0065	0070	0075	0080	0085	0090

Fig. 15-1. Comparative fuel costs. ("Hauck Industrial Combustion Data," Hauck Mfg. Co., Brooklyn.)

### DESIGN APPROACH FOR A FUEL-BURNING PLANT<sup>1</sup>

The intelligent approach to boiler-plant design demands a thorough survey of the fuels available in the location of the plant. The results of this survey will form a firm foundation on which to design the plant. Once the fuel has been determined, the science of plant design is well enough established to make it a relatively simple matter to design the plant on a guaranteed performance basis.

The more prevalent practice of building the plant first and then looking for a fuel or type of coal results in huge annual loss to industry. On the whole, large plants, because of the greater initial investment, are more careful of their fuel future than smaller plants; this is wrong as in the aggregate small plants burn much more coal than the larger plants (in one survey of 5,000 plants the average horsepower of mechanically fired boiler units was found to be only 300).

The outline following shows the successive steps which should be taken when a new power plant is contemplated as recommended by the Coal Bureau of the Upper Monongahela Valley Coal Association. It also gives a brief description of the major factors affecting the design of combustion equipment and the selection, valuation, and purchasing of fuel for steam-generating purposes.

#### Factors in Choosing a Fuel for a Contemplated Plant<sup>1</sup>

**I. Bituminous-coal selection.** The fuel investigation, considering competitive coals, should give weight to the following factors before a final decision is reached.

1. **Cost of coal production**, the major factor in determining cost of coal at the mines.
2. **Delivered cost of Btu as fired**, including transportation, is a governing factor in the modern steam plant.
3. **Market-price history and trends** are a guide to future price relationships.
4. **Resources or unmined reserves** should be extensive to assure future supplies.
5. **Relative availability** under both normal and unusual circumstances or demands, particularly important in boom or wartimes.
6. **Long-range government conservation** may be applied to limited reserves of scarce coals, especially when they are in demand for specific essential uses.

#### II. Prospective fuel supply.

1. **Primary selection** of one or more coals (by seams) in a producing region satisfies the major requirements developed under section I.
2. **Secondary selection** of one or more coals in another producing region which offer the best long-range competition for the primary selection.
3. **Prepare a fuel specification** to include the utilization of both the primary and secondary fuel, so that the plant to be built may utilize the range of quality and variation in performance characteristics of the sizes and grades that will be adaptable to the plant's anticipated load conditions.

#### III. Coal specification factors for use in design.

1. **Sizes and grades** for economical and satisfactory performance.
2. **Chemical quality.**
  - a. Uniformity of chemical quality, range (maximum-minimum).
  - b. Proximate analyses, including sulphur, Btu, and ash-softening temperature.
  - c. Ultimate analyses.
  - d. Ash analyses.
3. **Physical characteristics.**
  - a. Friability, resistance to degradation.

<sup>1</sup> Coal Bureau, Upper Monongahela Valley Association, *Ref. Bull.* 3, New York.

- b. Grindability, relative ease of pulverization.
- c. Size consist.
- d. Storage characteristics.
- 4. Performance characteristics.
  - a. Coking and caking tendency.
  - b. Clinkering and slagging characteristics.
  - c. Corrosive characteristics.
  - d. Ignition characteristics.

**IV. Selection and purchase of combustion equipment.** After the fuel investigation has determined what coal should be used, and the study determines the primary and secondary sources of supply, the fuel specification is written as a guide for the design of combustion equipment, which will permit flexibility in utilization, selection, and purchasing of coal.

1. **Complete coordination of design** must include transportation, unloading, handling, crushing, combustion equipment, and refuse disposal.

2. **Confidence, reliability, and experience** of the equipment manufacturer are major factors in selection.

3. **Utilization and purchasing latitude** are determined by basic design.

4. **Availability of skilled or unskilled labor** should be considered apart from basic economic factors.

5. **Operating reliability** is a major factor in cost (minimum outage).

6. **Dollar efficiency** (over-all cost per thousand pounds of steam) is more revealing than the efficiency of Btu conversion.

7. **Capital investment** is justification through long-range planning for dollar efficiency, *not* minimum first cost.

#### Fuels Selected for New Central-station Boilers<sup>1</sup>

Figure 15-2 shows the choice of fuel for 102 central stations reported by *Power* as being installed or planned between September, 1946, and June, 1947. Of the 102

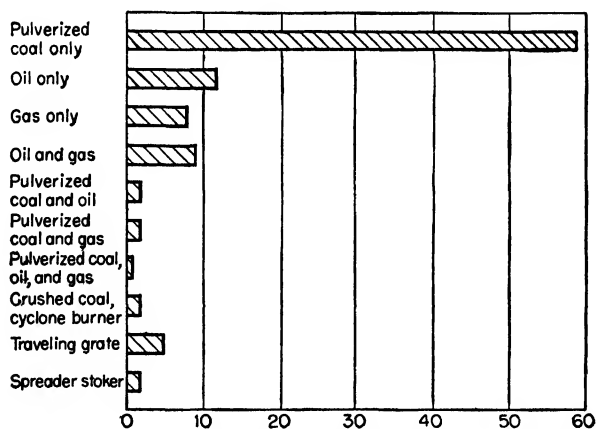


FIG. 15-2. Fuel selection of new central stations, 1946 to 1947. ("Power" survey, June, 1947.)

boilers, 59 are pulverized-coal fired, 12 oil fired, 8 gas fired, 7 stoker fired, and the remaining 16 are fired by a combination of fuels.

<sup>1</sup> *Power*, June, 1947.

Table 15-5. Selection of Burning Equipment by Industry Classification<sup>1</sup>

Industry	Type of firing selected				
	Pulverizers	Spreader stokers	Traveling grates	Underfeed stokers	Total
Iron and steel .. . . .	4	2	2	..	8
Food and kindred products ..	1	16	..	1	18
Chemical and allied products...	10	22	1	3	36
Paper and allied products.	20	16	2	1	39
Textiles, fabrics, and their products	5	2	1	1	9
Automobile and accessory parts	9	22	..	2	33
Locomotive and railroad equipment	3	..	2	..	5
Rubber products	3	1	..	..	4
Public utilities	33	7	3	..	43
Municipal utilities	5	8	1	2	16
Distilled spirits and brewing	9	..	..	..	9
Educational institutions .. . .	..	2	..	1	3
Totals	102	98	12	11	223

<sup>1</sup>TOHEY, J. E., "A Fuel Engineering Study of Some Recent Boiler Installations," ASME annual meeting, New York, Dec. 3, 1946. Based upon an analysis of 254 boiler units contracted for in 1945-1946 in the Northeastern United States and Great Lakes region only, and ranging in size between 15,000 and 1,000,000 lb per hr.

Table 15-6. Comparative Annual Costs per Kilowatt of Net Plant Capacity<sup>1</sup>  
(With various steam pressures. Based on the ultimate installation of four 75,000-kw, 1,800 RPM single-cylinder turbine generator units)

Psig	Temp, deg F	Annual capacity factor, per cent						
		5	10	20	40	60	80	100
Fuel at \$0.90/bbl								
400	750	7.92	8 65	10 10	13 00	15 92	18 83	21.73
650	825	7.92	8.60	9.97	12 67	15 41	18 13	20 86
850	900	8 09	8 74	10 05	12.66	15.28	17.89	20.51
1,250	900	8 31	8 96	10 24	12 81	15 37	17 94	20.51
Fuel at \$1.00/bbl								
400	750	8.07	8 88	10 49	13 72	16.96	20 19	23 42
650	825	8.07	8.82	10.34	13.36	16.39	19.41	22.44
850	900	8 23	8 95	10 41	13.31	16.22	19.12	22.03
1,250	900	8 45	9.17	10 59	13 45	16 30	19 15	22.01
Fuel at \$1.10/bbl								
400	450	8.22	9.11	10 88	14 44	18 00	21 57	25 11
650	825	8.22	9.04	10.71	14 05	17 37	20.69	24.02
850	900	8 37	9 17	10.77	13.96	17.16	20.35	23.55
1,250	900	8 59	9 38	10 94	14 09	17.23	20.36	23.51

NOTE: Bold-face numbers are lowest in cost for each capacity factor.

<sup>1</sup>ROWSE, WILLIAM C., Some Features of the Harbor Steam Plant of the Los Angeles Bureau of Power and Light, *Mech. Eng.*, November, 1942, pp. 773-776.



Of interest are two boilers reported to be fitted with cyclone burners similar to the experimental installation at Calumet Station, of the Commonwealth Edison Co.

Installations for pulverized-coal burning are designed 70 per cent with dry bottoms and 30 per cent with slag taps.

Furnace heat releases for all types of firing average about 22,000 Btu/hr/cu ft. For pulverized-coal firing, they average slightly less than 20,000 Btu/hr/cu ft, with the highest 26,600 Btu and the lowest 12,300.

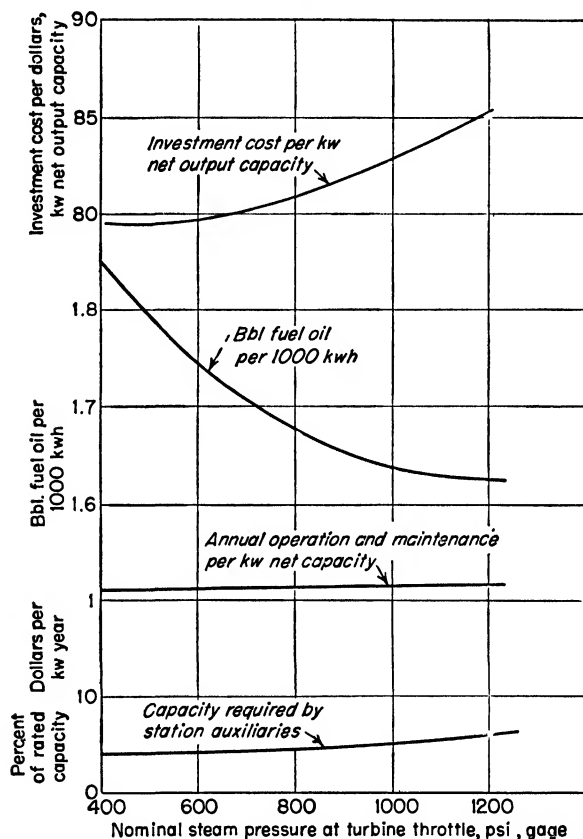


FIG. 15-3. Effect of steam pressure on various cost items of turbine-steam plant of four 75,000-kw units. (Rowse, William C., *Some Features of the Harbor Steam Plant of the Los Angeles Bureau of Power and Light*, *Mech. Eng.*, November, 1942, pp. 773-776.)

About 54 per cent of the steam generators have both air heaters and economizers, 45 per cent have air heaters only, and only about 1 per cent have no auxiliary heating surface. Tubular air heaters predominate with 55 per cent; 41 per cent are of the regenerative type; and the remaining 4 per cent, the plate type.

#### Economic Effect of a Range of Pressures and Temperatures

Figure 15-3, as based on a study by W. C. Rowse,<sup>1</sup> compares the effect of a range of steam pressures and temperatures at the throttle of the same 75,000-kw steam-turbine

<sup>1</sup> ROWSE, WILLIAM C., *Some Features of the Harbor Steam Plant of the Los Angeles Bureau of Power and Light*, *Mech. Eng.*, vol. 64, No. 11, pp. 773-776, November, 1942.

generating units. It shows (1) that, while the investment cost advances at an increasingly rapid rate as the steam pressure and temperature are increased, the fuel consumption goes down at a decreasing rate; (2) that the operation and maintenance expense is practically uniform for all pressures; and (3) that the power required by auxiliaries increases with the rise in steam pressure.

In Table 15-6, which is a report of the same study, boldface numerals indicate the most economical steam conditions over a range of annual capacity factors from 5 to 100 per cent.

### FACTORS IN THE PURCHASE OF COAL<sup>1</sup>

In order to establish some values for coal selection, considerable work has been done by the Coal Committee of the National Association of Purchasing Agents. For example, their *Bulletin 21, Factors Recommended for Consideration in the Selection of Coal*, which has been reproduced in its entirety (Tables 15-10 to 15-19), is a most comprehensive correlation between all practical coal characteristics and several hundred factors of use in various industries and on different equipment in several conditions of design and repair. However, as Gehring points out, there can be no single standard of coal selection because of the extreme complexity of both the fuel and its uses. In all cases in the purchase of coal for fuel, the important element is to obtain the largest number of heating units per unit of cost. To this end Tables 15-7 and 15-8, with accompanying text, have been prepared as an approximate guide to a determination of the true "use value" of a fuel. Among the important points that these show is that the true value of a coal is directly affected by such secondary factors as freight rate which can so change the economics that a coal that proved most advantageous in one location might be economically unsuited to another. In addition, even the cost is not absolutely controlling because of the necessity of taking into consideration the applicability of the coal in the particular utilization equipment and conditions available. To aid in an evaluation of this factor, a considerable amount of material on coal selection has been included in the several discussions of individual equipment in this volume.

The only true way to evaluate coal is by test in your own equipment. Unfortunately, tests sufficiently complete as to be conclusive are very costly, but approximate results can be obtained by trying a few cars and observing such factors as appearance, how it unloads, and how it operates from a firing standpoint. Satisfactory results by this method, however, are not necessarily indicative of the best economy. Some coals, capable of excellent performance, may be high in ash, low in heat value, and really expensive in terms of cost per million Btu. A further problem in connection with plant trials is to be sure that the coal under consideration is not being mixed with the previous fuel, such as in the bunkers or at other storage or handling points. This usually presents a serious problem when the coal is received by barge since, unless a full barge of at least 18 or 20 cars is accepted and loaded simultaneously, segregation to the point of securing a dependable test will be virtually impossible.

In general, a great deal of unnecessary work of testing can be eliminated by comparing or evaluating the coal or coals offered against coals whose quality and performance are definitely known. If the analysis of the coal offered indicates that it can probably be used, the buyer can determine quite readily whether or not it would be worth while to test the coal.

**Coal Analyses.** One of the serious problems confronting a coal buyer is to secure sufficient *reliable* advance information to enable a determination of the relative reliability of the coal. The usual qualifications offered on behalf of any particular

<sup>1</sup> From GEHRING, WILLIAM H., "How to Buy Coal and Fuel Oil," National Association of Purchasing Agents.

coal are mine name, location, coal seam mined, railroad connections, and analysis. Unfortunately, coal seams are not uniform, and coal from a given seam at one location may differ quite materially from another coal mined in the same seam a short distance away. The seam identification, however, may give some indication as to the nature of the coal. The best indicator is the analysis, although those used by salesmen are only too frequently back-dated to the point of being ancient. Three precautions should thus be used before accepting a coal analysis for consideration: (1) ask for the date or approximate date of the sample; (2) be sure that the analysis given is one for commercial coal as loaded on cars, as distinguished from a mine or face sample which may be considerably different because of having been secured from the heart of a coal seam; (3) rough check the analysis by comparing it with Bureau of Mines, or equally reliable, determinations from the same locality (a section on coal analysis is included in Chap. 4).

If any factor of the analysis presented is very far out of the range given for the locality in question, it can at least be regarded with caution. Further, several items of an analysis are roughly correlated for all coals; thus the higher the Btu, the lower the ash; carbon is a function of the ash and volatile; and ash fusion, coking, caking, and other such general characteristics are very likely, although by no means always, apt to follow the region of mining (a section on the geographical characteristics of coals will be found in Chap. 4). A little experience followed by careful examination of submitted analyses should soon teach a buyer to weed out authentic analyses from synthetic or careless versions.

**Sampling Coal.** As has been inferred, face or mine samples are all but meaningless to the prospective purchaser; spot car samples are also analogous to judging a box of strawberries by the top layer. The best method of obtaining a representative sample is from the coal in motion on a conveyor belt.

**Buying Coal on Contract.** Coal contracts should include identity of the coal and specification of size, price, shipping point, and railroad. While it is also well to include provisions concerning quality, penalty and bonus clauses very frequently boomerang and are generally disliked by both coal operators and shrewd purchasers. Wage clauses are also customary, allowing increases or decreases in proportion to changed labor costs.

**Supply and Storage.** It is not possible to prescribe accurate limits as to the quantity of coal which should be purchased from each supplier, or how many suppliers should be selected to furnish the coal requirements. These factors are largely dependent upon the total quantity of coal required, the capacity of the supplying mine, the responsibility of the coal producer, and the storage capacity and habits of the plant. It is of importance to note that many interruptions of production in mining are purely local in nature and do not cover the entire industry. Thus several sources of supply are much less likely to be interrupted than one; the importance of this to the plant, however, depends on the storage factors mentioned (proper methods of storage will be found in Chap. 18).

#### Comparison of Coals Having Different Ash Contents

In comparing coals of different ash content, a number of factors should be considered, including (1) possible effect upon plant performance and efficiency, (2) ability to handle the increased quantity of the higher ash coal which will be needed, (3) gross and net effect on the cost of coal and freight, and (4) ability and cost of handling the increased amount of ash and refuse.

The magnitude of the effect of higher ash content on plant performance varies greatly with such factors as load, type of equipment, and basic plant design. For example, if the plant was originally designed for relatively high ash coal, its operation

will be usually but little, if any, affected by changes in ash content within reasonable ranges; if the plant design contemplated low-ash coal, however, there may not be a sufficient reserve capacity to handle the greater bulk of coal required. Naturally, a great deal also depends on the magnitude of the difference in the ash content of the two coals. It is thus virtually impossible to generalize, although, under the individual discussions of equipment elsewhere in this book, the effect of changes in ash content is usually discussed.

Likewise, ability to handle increased quantities of a higher ash coal together with the augmented amount of ash and refuse depends entirely upon the individual plant. Nevertheless, it should be carefully considered with particular reference to any increased costs for either equipment or personnel which may be involved.

**Increased Quantity of Fuel Required.** The principal and most important difference in the purchase of lower ash coal lies in the fact that, even at the same efficiency, increased amounts of coal must be bought transported, handled, and fired in order to deliver the same number of heat units, or Btu, to the boilers.

**Table 15-7. Increased Cost of Coal or Freight Due to Purchase of Higher Ash Coal**

(Body of table in cents additional cost per ton replaced)

Percentage points difference in ash contents	Price of coal or freight (dollars/net ton)								
	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
1	3 0	3 6	4 2	4 8	5 4	6 0	6 6	7 2	7 8
2	6 25	7 5	8 75	10 0	11 25	12 5	13 75	15 0	16 25
3	9 5	11 4	13 3	15 2	17 1	19 0	20 9	22 8	24 7
4	12 75	15 3	17 85	20 4	22 95	25 5	28 05	30 6	33 15
5	16 25	19 5	22 75	26 0	29 25	32 5	35 75	39 0	42 25
6	19 5	23 4	27 3	31 2	35 1	39 0	42 9	46 8	50 7
7	23 0	27 6	32 2	36 8	41 4	46 0	50 6	55 2	59 8
8	26 5	31 8	37 1	42 4	47 7	53 0	58 3	63 6	68 9
9	30 25	36 3	42 35	48 4	54 45	60 5	66 55	72 6	78 65
10	33 5	40 2	46 9	53 6	60 3	67 0	73 7	80 4	87 1
11	37 0	44 4	51 8	59 2	66 6	74 0	81 4	88 8	96 2
12	40 5	48 6	56 7	64 8	72 9	81 0	89 1	97 2	105 3
13	44 25	53 1	61 95	70 8	79 65	88 5	97 35	106 2	115 05
14	47 5	57 0	66 5	76 0	85 5	95 0	104 5	114 0	123 5

**Example:** Assume that a 10 per cent ash coal is being bought for \$4.50 with \$4 00 freight, and that a change is made to 13 per cent ash coal with the same cost and freight rate. The percentage points difference is 3 (13 - 10) for which the table shows that the amount of coal which will have to be purchased to equal the former heat value will cost 17.1 cents more per net ton and that the freight will be 15.2 cents more, a total of 32.3 cents per ton more for the same heat value. To this must be added the increased cost of handling the higher ash coal at prevailing plant costs.

In those rare cases where the volatile matter and all other characteristics of the two coals are the same, the relation between the quantities required on account of different ash contents may be expressed by the following formula:

$$\text{Tons of higher ash coal required to replace 1 ton of lower ash coal} = \frac{100 - A_l}{100 - A_h}$$

where  $A_l$  = per cent ash in lower ash coal

$A_h$  = per cent ash in higher ash coal

**Example:** Given a 20 per cent ash and a 10 per cent ash coal (of the same volatile), the above equation gives a result of 1.125 to indicate that 1.125 tons of the higher ash coal would be required to replace each ton of the lower ash coal.

Where actual Btu values for the two coals in question are available, it is preferable to use them instead of the above formula; otherwise this will provide a good approximation of the relative quantities of fuel required.

The ratio as obtained either from the formula or from a direct comparison of Btu may next be applied to both the per ton cost of the fuel and to the freight rate to deter-

**Table 15-8. Per Cent Increase in Coal Required Due to Increased Ash Content**  
(Based on actual heat value of coal at various ash percentages rather than upon mathematical relation alone)

Higher ash coal, per cent ash content	Lower ash coal, per cent ash										
	6	7	8	9	10	11	12	13	14	15	16
7	1 2										
8	2 5	1 2									
9	3 8	2 5	1 2								
10	5 1	3 8	2 5	1 2							
11	6 5	5 1	3 8	2 5	1 2						
12	7 8	6 5	5 1	3 8	2 5	1 2					
13	9 2	7 8	6 5	5 1	3 8	2 5	1 2				
14	10 6	9 2	7 8	6 5	5 1	3 8	2 5	1 2			
15	12 1	10 6	9 2	7 8	6 5	5 1	3 8	2 5	1 2		
16	13 4	12 1	10 6	9 2	7 8	6 5	5 1	3 8	2 5	1 2	
17	14 8	13 4	12 1	10 6	9 2	7 8	6 5	5 1	3 8	2 5	1 2
18	16 2	14 8	13 4	12 1	10 6	9 2	7 8	6 5	5 1	3 8	2 5
19	17 7	16 2	14 8	13 4	12 1	10 6	9 2	7 8	6 5	5 1	3 8
20	19 0	17 7	16 2	14 8	13 4	12 1	10 6	9 2	7 8	6 5	5 1

**Example:** If a 9 per cent ash coal has been used and a 16 per cent ash coal is contemplated, the chart shows that 9.2 per cent more coal will have to be bought, transported, and handled to furnish the same heat value as formerly.

**Table 15-9. Approximate Heat Value of Anthracite with Various Volatile and Ash Contents**

(Figures in body of table are Btu, dry basis)

Ash content, per cent, dry basis	Volatile matter, per cent, dry basis						
	3	4	5	6	7	8	9
8	13,650	13,750	13,825	13,910	14,000	14,100	14,200
9	13,500	13,575	13,660	13,750	13,850	13,950	14,040
10	13,310	13,420	13,500	13,580	13,670	13,760	13,860
11	13,160	13,250	13,350	13,420	13,500	13,600	13,690
12	13,000	13,090	13,170	13,250	13,340	13,430	13,520
13	12,830	12,900	13,000	13,090	13,170	13,250	13,350
14	12,670	12,750	12,820	12,910	13,000	13,090	13,180
15	12,500	12,590	12,675	12,750	12,830	12,910	13,000
16	12,350	12,425	12,500	12,580	12,660	12,750	12,870
17	12,200	12,275	12,350	12,420	12,500	12,575	12,660
18	12,050	12,125	12,200	12,260	12,350	12,420	12,500
19	11,900	11,950	12,050	12,100	12,180	12,260	12,340
20	11,750	11,800	11,900	11,950	12,020	12,100	12,180

mine the change in the delivered price of the coal. On a percentage basis, the change will remain fixed. Thus if, as is shown graphically in Table 15-8, 13.4 per cent more coal will be required if it contains 20 per cent than if it contains 10 per cent ash, this 13.4 per cent increase in cost will apply regardless of the coal price or freight rate.

However, it is important to note that the dollar increase in both coal costs and freight rises in direct proportion to the unit cost of either. Thus, for the example given of 20 and 10 per cent ash, if the freight rate is \$2.50 per ton, an equivalent amount of 20 per cent ash coal will cost 33.5 cents more for transportation, but if the freight rate is \$5, it will cost 67 cents more. While this is a very obvious relationship, it is stressed here because of its importance; *viz.*, if the plant had been at a \$2.50 rate from the mine, only 33.5 cents more could have been afforded for the 10 per cent ash coal before the cost of the two was equalized; but, if the plant had been located at a \$5 freight distance, up to 67 cents could have been paid for the better coal without any chance in loss in annual operating cost.

Table 15-7 shows the increase in cents for various differences in ash contents.

### Relative Importance of Factors in the Selection of Coal<sup>1</sup>

Acting with the cooperation of the National Association of Purchasing Agents, Subcommittee VI<sup>2</sup> of the ASTM prepared a tabulation of the various physical and chemical factors which affect the selection of coal.

This was combined with a tabulation showing the various industrial and domestic uses of coal, subdivided according to distinct types of equipment and conditions of use which might affect coal selection. The resultant seven coal selection charts are reproduced as Tables 15-10 to 15-19, inclusive.<sup>3</sup>

Due consideration was given to the assignment of numerical values or actual specification to each space on the chart but was rejected for several reasons. The matter of securing committee agreement on specifications for more than 7,000 separate items was by no means the only problem. More important is the fact that no ready-made classification or set of specifications can possibly replace the judgment and resourcefulness of an experienced combustion engineer or fuel technologist, or the usual need for full-scale plant tests under the exact conditions of use before a final decision is made.

Attention is called to the fact that those who filled in the questionnaires were asked to do this on the basis of the technical factors involved, without regard to economic factors such as the kinds and prices of coals available in various territories, freight rates, etc. Obviously, the economic factors existing at each individual consuming point must always be considered when coal is selected.

These charts have been drawn up for average conditions, and, when applying them, a corrective factor may have to be applied, especially to allow for new developments in combustion engineering. For example, it will be noted from Table 15-12, "Stationary Steam Generation, Stoker-fired," that, in the case of underfeed stokers, the importance of fusing point of ash for most of the combustion variations is one grade less when water-cooled tuyères are used.

The charts in their present form will be a helpful guide both to the consumer who wishes to know what coal characteristics should be considered in order to make the proper selection of coal for his particular needs, and to the coal producer who wishes to reach those markets for which his products are best suited. It is not claimed that the ratings on the charts are accurate in every detail, but they do represent, in each instance, the average present opinion of a number of fuel technologists. Space has not

<sup>1</sup> "Factors Recommended for Consideration in the Selection of Coal," issued by National Committee on Coal of the National Association of Purchasing Agents, Thomas W. Harris, Jr., chairman, 1936. Reprinted by permission of the copyright owners.

<sup>2</sup> The Technical Committee on Classification of Coal is a working committee of the American Standards Association Sectional Committee on Classification of Coal, which is sponsored by the ASTM.

<sup>3</sup> Briefly summarized, the method of compiling the charts consisted of sending blank forms or questionnaires to a carefully selected group of technologists for their composite opinion of the importance of each factor and subdivision. The committee, in compiling the replies, carefully weighted them according to the experience of the correspondents in each respective field.

permitted the inclusion of every coal-selection factor. For example, ultimate analysis has not been included, although it has had successful use for special coal-selection purposes, and is also used in heat-balance calculations; nor has it been possible to show the influence of the factors upon each other.

The data have been arranged in the form of ten charts, as follows:

- Table 15-10, Stationary Steam Generation, Hand-fired Bituminous
- Table 15-11, Stationary Steam Generation, Hand-fired Anthracite
- Table 15-12, Stationary Steam Generation, Spreader, Overfeed, and Underfeed Stokers
- Table 15-13, Stationary Steam Generation, Traveling- and Chain-grate Stokers
- Table 15-14, Stationary Steam Generation, Pulverized-coal and Dry-Bottom Types
- Table 15-15, Stationary Steam Generation, Pulverized-coal and Wet-bottom Types
- Table 15-16, Coke and Gas Making
- Table 15-17, Ceramic Products
- Table 15-18, Miscellaneous, Cement Burning, Lime Burning, Locomotive Fuel, Metallurgical, Foundry Facings, Colloidal, Industrial Processes
- Table 15-19, Domestic, Cargo, and Bunker

### Detailed Reference Notes and Their Identifying Symbols

(For Tables 15-10 to 15-19)

All notes appearing on any coal selection chart are included in the following list, and carry symbols identical with those appearing on the charts.

a. Factors in coal selection are necessarily limited by the delivered cost to consuming points on an economic basis of coals available in the various territories in the United States and Canada which have been subdivided in a paper presented before the AIME in February, 1933, on "Use Classification for Stationary Steam Generation" as follows:

- |                        |                                     |
|------------------------|-------------------------------------|
| 1. Eastern New England | 7. South Atlantic                   |
| 2. Middle Atlantic     | 8. Outlying fields in United States |
| 3. Pittsburgh          | 9. Eastern Canadian                 |
| 4. Central             | 10. Central Canadian                |
| 5. Middle West         | 11. Western Canadian                |
| 6. Upper Lakes         |                                     |

aa. Combustion variables, in part or as a whole, may affect the selection of coals for nearly every use, such as:

- |                                     |  |
|-------------------------------------|--|
| 1. Excessive load                   | 5. Improper design of combustion chamber |
| 2. Undersize of combustion chamber  | 6. High cost of ash removal              |
| 3. Unfavorable firebrick conditions | 7. Insufficient grate to heating area    |
| 4. Insufficient draft               |  |

aaa. Combustion variables, in part or as a whole, may affect the selection of coals for nearly every use, such as:

- |   |  |
|---|--|
| 1. Excessive rates of burning per furnace | 5. High cost of clinkering and ash removal |
| 2. Unfavorable firebrick conditions       | 6. Undesirable fly ash in furnace gases    |
| 3. Insufficient draft                     | 7. Improper kiln atmosphere required       |
| 4. Insufficient grate area                | 8. Type of fuel bed                        |

b. Firebrick in the combustion chamber may affect the selection of coal because of its chemical composition, its fusing point, or the resistance the firebrick has to abrasion.

bb. In general, cooler sides or bottom of the combustion chamber permit the use of coals of lower fusion point of ash, in the following order: (1) refractory, (2) air-cooled, and (3) water-cooled.

bbb. The types of "checkers" or regenerators are closely connected with and affect the type of coal used because of the clogging effect of varying types of ash deposits.

bbbb. Committee of Ten, Coal and Heating Industries, suggests a further breakdown in this use according to different types of heating boilers and furnace-combustion variables and the difference in operation of warm-air gravity plants and warm-air forced circulation; also the combustion variables as applied to hot-water and steam boilers. They also advise that coal selection in this use is dependent to an important degree on mixture, air, time and temperature, furnace volume, and net flame clearance, especially with respect to underfeed stoker firing.

c. Bright or common, splint, cannel, and boghead or algal coals, as defined by the Coal Classification Committee.

d. According to the degree of metamorphism, or progressive alteration in the natural series from lignite to anthracite, with the limits of fixed carbon or volatile matter and Btu on the mineral-matter-free basis. Agglomerating and weathering properties enter into this classification in certain groups. In accordance with ASTM Tentative Specifications D388-34T as revised.

e. According to quality, as determined by calorific value, ash and sulphur content, and ash-softening temperature. In accordance with ASTM Tentative Specifications D389-34T.

f. Commercial size, supplemented by actual screen analysis made as follows:

Anthracite: In accordance with ASTM Standard D-310-34.

(Continued on p. 517.)

**Table 15-10. Coal Selection Chart for Stationary Steam Generation and Hand-fired Bituminous Coal<sup>1</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

Reference notes <sup>2</sup>	Classification		Specific chemical properties of coal										Specific physical properties <sup>2,3</sup>				General														
	By type	By rank	By grade	Ash per cent	Fusion point										Sulphur	Caking	Sp gr	Storage	Handling	Full- ver- nized											
					Chemical composition	Initial temp	Soft temp	Fluid temp	Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus																	
c	d	e	f	g	h	i	j	k	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h

**Stationary Grates**

Normal conditions	c	—	c	b	c	c	c	c	c	c	c	c	c	c	c	—	—	—	c	c	—	—	—	—	—	c	c	c	c	c	c	c
Excessive load	c	—	b	a	b	c	b	b	b	b	b	b	b	b	b	c	—	—	c	b	—	—	—	—	—	c	c	b	b	—	c	c
Undersized combustion chamber	c	—	a	a	c	c	c	c	c	c	b	b	b	b	b	b	—	—	c	c	—	—	—	—	—	c	c	c	c	—	b	c
Insufficient grate to heating area	c	—	a	a	b	b	b	b	a	b	a	a	a	c	c	b	—	—	c	c	—	—	—	—	—	c	—	b	b	—	b	c
Unfavorable firebrick conditions <sup>1</sup>	c	—	c	a	c	c	c	c	b	b	b	b	b	b	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c
Insufficient draft	c	—	a	a	a	c	c	c	b	b	b	b	b	b	c	c	—	—	c	b	—	—	—	—	—	c	c	c	c	—	c	c
Unskilled labor	c	—	b	a	c	c	b	c	b	b	b	b	b	b	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c
High cost of ash removal	c	—	b	a	c	b	c	c	a	c	b	b	b	c	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c

**Shaking or Dumping Grates**

Normal conditions	c	—	c	b	c	c	c	c	c	c	c	c	c	c	c	—	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c
Excessive load	c	—	b	a	b	b	b	b	b	b	b	b	b	b	b	b	—	—	c	b	—	—	—	—	—	c	c	b	b	—	c	c
Undersized combustion chamber	c	—	a	a	c	c	c	c	c	c	b	b	b	b	b	b	—	—	c	c	—	—	—	—	—	c	c	c	c	—	b	c
Insufficient grate to heating area	c	—	a	a	b	b	b	c	a	b	a	a	a	c	c	b	—	—	c	c	—	—	—	—	—	c	c	b	b	—	b	c
Unfavorable firebrick conditions <sup>1</sup>	c	—	c	a	c	c	c	c	b	b	b	b	b	b	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c
Insufficient draft	c	—	a	a	a	b	c	c	b	b	b	b	b	b	c	c	—	—	c	b	—	—	—	—	—	c	c	c	c	—	c	c
Unskilled labor	c	—	b	a	c	c	b	c	b	b	b	b	b	b	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c
High cost of ash removal	c	—	b	a	c	b	c	c	a	b	b	b	b	c	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	c

**Downdraft**

Normal conditions	c	—	b	b	b	c	c	b	c	b	c	c	c	c	c	—	—	—	b	b	—	—	—	—	—	c	c	c	c	—	c	c
Excessive load	c	—	b	b	b	b	c	b	a	c	c	c	c	b	—	c	—	—	a	a	—	—	—	—	—	c	b	b	b	—	b	c
Undersized combustion chamber	c	—	b	b	b	b	c	c	b	c	b	c	b	c	—	c	—	—	b	b	—	—	—	—	—	c	c	c	c	—	b	c
Insufficient grate to heating area	c	—	a	a	b	b	c	b	b	c	b	—	—	—	—	c	—	—	b	b	—	—	—	—	—	c	c	b	b	—	b	c
Unfavorable firebrick conditions <sup>1</sup>	c	—	a	a	b	b	c	c	b	c	b	—	—	—	—	c	—	—	b	b	—	—	—	—	—	c	c	c	c	—	c	c
Insufficient draft	c	—	a	a	b	b	c	c	b	c	b	—	—	—	—	c	—	—	b	b	—	—	—	—	—	c	c	c	c	—	c	c
Unskilled labor	c	—	b	a	b	c	c	b	c	b	b	—	—	—	—	c	—	—	b	b	—	—	—	—	—	c	c	c	c	—	c	c
High cost of ash removal	c	—	b	a	b	b	c	c	b	c	b	—	—	—	—	c	—	—	b	b	—	—	—	—	—	c	c	c	c	—	c	c

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 510-517.



**Table 15-11. Coal Selection Chart for Stationary Steam Generation and Hand-fired Anthracite Coal<sup>1</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

Reference notes <sup>2</sup>	Classification										Specific chemical properties of coal										Specific physical properties <sup>4,k</sup>						General										
	By type		By rank		By grade		Moisture per cent	As sampled	Chemical composition	Fusion point		Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus	Caking		Sp gr	Plasticity	Spontaneous combustion	Weathering	Size stability	Frability	Grindability	Smoke, potential	Universal limitations									
	Class	Group	Classification	Size	Impurities	Deviation				Initial temp	Soft temp							Fluid temp	Sulphur										Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Storage	Handling	Pulverized
c	d	d	e	f	g	h	h	j	h	h	h	h	h	h	k	h	l	m	n	o	p	q	r	s	t	u	v	w	x	yy							

## Stationary Grates

Normal conditions.	—	—	—	b	c	c	c	c	c	c	c	c	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Excessive load	—	—	—	a	b	b	b	c	b	c	b	b	c	c	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Improper furnace design	—	—	—	a	b	c	c	c	b	c	b	b	c	c	c	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Insufficient grate to heating area	—	—	—	a	b	b	c	c	b	c	b	b	b	b	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Unfavorable firebrick conditions <sup>b</sup>	—	—	—	a	c	c	c	c	c	c	b	b	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Insufficient draft	—	—	—	a	b	c	c	c	b	c	b	b	c	c	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
High cost of ash removal	—	—	—	a	c	a	c	c	a	c	c	c	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—

## Shaking and Dumping Grates and Semistokers

Normal conditions	—	—	—	b	c	c	c	c	c	c	c	c	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Excessive load	—	—	—	a	b	b	b	c	b	c	b	b	c	c	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Improper furnace design	—	—	—	a	b	c	c	c	b	c	b	b	c	c	c	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Insufficient grate to heating area	—	—	—	a	b	b	c	c	b	c	b	b	b	b	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Unfavorable firebrick conditions	—	—	—	a	c	c	c	c	c	c	b	b	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
Insufficient draft	—	—	—	a	a	b	c	c	b	c	b	b	c	c	b	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—
High cost of ash removal	—	—	—	a	c	a	c	c	a	c	c	c	—	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	c	c	—	—

<sup>1</sup> National Association of Purchasing Agents<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

**Table 15-12. Coal Selection Chart for Stationary Steam Generation, Stoker-fired (Except Traveling Grates)<sup>1,a</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance, — = not important. No entry = to be developed)

	Classification							Specific chemical properties of coal							Specific physical properties <sup>a,b</sup>							General											
	By rank			By grade				Ash per cent	Fusion point			Sulphur	Caking			Sp gr	Storage	Handling	Pul-verized														
	By type	Class	Group	Classification	Size	Impurities	Deviation		Moisture per cent	Chemical composition	Initial temp		Soft temp	Fluid temp	Volatile per cent					Fixed carbon	Btu/lb	As sampled per cent	Formas	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering
Reference notes <sup>a</sup>	c	d	a	e	f	g	i	h	h	j	h	h	h	h	h	h	h	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
Spreader Stokers																																	
Normal conditions	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Excessive load	c	c	c	c	b	c	c	c	b	c	c	b	b	c	c	b	c	—	—	—	—	—	—	—	—	c	c	c	c	—	a	—	
Undersized combustion chamber	c	c	c	c	b	c	c	c	c	c	c	c	c	b	b	c	c	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Insufficient grate to heating area	c	c	c	c	b	c	c	c	b	c	c	c	c	c	c	b	—	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Unfavorable firebrick conditions <sup>b</sup>	c	c	c	c	b	c	c	c	c	b	b	b	b	c	c	c	c	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Insufficient draft	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
High cost of ash removal	c	c	c	c	c	c	c	c	b	b	c	c	c	c	c	c	c	—	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Slagging of boiler tubes	c	c	c	b	c	b	c	c	c	b	c	b	b	c	c	c	c	c	—	—	—	—	—	—	—	c	c	c	c	—	b	—	
Overfeed Stokers																																	
Normal conditions	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	—	
Excessive load	c	b	b	b	b	b	c	b	b	b	c	b	b	b	b	b	c	—	c	b	—	—	—	—	—	c	c	b	b	—	b	—	
Undersized combustion chamber	c	b	b	b	c	c	c	c	c	b	b	b	b	b	b	c	—	—	b	c	—	—	—	—	—	c	c	c	c	—	b	—	
Insufficient grate to heating area	c	b	b	a	b	b	c	b	b	b	b	a	b	c	c	b	—	—	c	c	—	—	—	—	—	c	c	c	c	—	b	—	
Unfavorable firebrick conditions	c	b	b	b	c	c	c	c	b	b	b	b	b	b	b	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	—	
Insufficient draft	c	b	b	b	b	c	c	c	c	b	b	b	b	b	b	c	—	—	c	b	—	—	—	—	—	c	c	c	c	—	c	—	
High cost of ash removal	c	b	b	b	c	c	c	c	a	c	b	b	b	c	c	c	—	—	c	c	—	—	—	—	—	c	c	c	c	—	c	—	
Underfeed Stokers <sup>b,b</sup>																																	
Normal conditions	b	b	c	a	b	b	c	c	c	c	a*	a*	b*	c	c	b	c	—	—	c	c	c	—	—	—	c	c	c	c	—	c	—	
Excessive load	b	b	b	a	b	b	b	b	b	b	a*	a*	b*	b	b	b	c	—	c	c	—	—	—	—	—	b	c	b	b	—	c	—	
Undersized combustion chamber	b	b	b	a	b	b	c	c	c	c	b*	b*	b*	b	b	c	c	—	c	c	—	—	—	—	—	b	c	c	b	—	b	—	
Insufficient grate to heating area	b	b	b	a	b	b	c	c	b	c	a*	a*	b*	c	c	b	c	—	c	b	c	—	—	—	—	b	c	b	b	—	c	—	
Unfavorable firebrick conditions	b	b	c	a	b	b	c	c	c	b	b*	a*	b*	c	c	c	c	c	—	c	c	c	—	—	—	c	c	c	b	—	c	—	
Insufficient draft	b	b	c	a	b	b	c	c	b	c	b*	b*	c*	c	c	b	c	—	c	b	c	—	—	—	—	b	c	c	b	—	c	—	
High cost of ash removal	b	b	c	a	b	b	c	c	a	c	b*	b*	b*	c	c	c	c	—	c	c	c	—	—	—	—	c	c	c	c	—	c	—	
Preheated air	b	b	b	a	b	b	c	c	c	b	a*	a*	a*	c	c	c	c	—	c	c	c	—	—	—	—	c	c	c	c	—	c	—	
Slagging of boiler tubes	b	b	b	a	b	b	c	c	b	b	b*	b*	b*	c	c	c	c	—	c	c	c	—	—	—	—	c	c	c	c	—	c	—	

<sup>1</sup> National Association of Purchasing Agents.

<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

\* With water-cooled tuyères the fusion point of the ash is one grade less important.

**Table 15-13. Coal Selection Chart for Stationary Steam Generation, Traveling- or Chain-grate Stokers<sup>1, a, b</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance. — = not important. No entry = to be developed)

	Classification							Specific chemical properties of coal							Specific physical properties <sup>2,4</sup>							General																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	By rank			By grade				Ash per cent	Fusion point					Sulphur	Caking			Sp gr	Storage	Handling	Pulverized																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
	By type	Class	Group	Classification	Size	Impurities	Deviation	Moisture per cent	As sampled	Chemical composition	Initial temp	Soft temp	Fluid temp	Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering	Size stability	Friability	Grindability	Smoke, potential	Universal limitations																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

**Table 15-14. Coal Selection Chart for Stationary Steam Generation, Pulverized-coal, Dry-bottom Types<sup>1,a,b</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

	Classification						Specific chemical properties of coal						Specific physical properties <sup>1,2</sup>						General																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
	By type	Class	Group	By rank		By grade	Ash per cent	Fusion point		Sulphur	Caking		Sp gr	Storage	Handling	Pulverized																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
				Classification	Size			Initial temp	Soft temp		Fluid temp	Volatile per cent					Fixed carbon	Btu/lb																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
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Moisture per cent	As sampled	Initial temp	Soft temp	Fluid temp	Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion					Weathering	Size stability	Friability	Grindability	Smoke, potential	Universal limitations																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
Reference notes <sup>3</sup> .	c	d	d	e	f	g	h	h	j	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

**Table 15-15. Coal Selection Chart for Stationary Steam Generation, Pulverized-coal, Wet-bottom Types<sup>1a,bb</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

	Classification										Specific chemical properties of coal										Specific physical properties <sup>4a</sup>						General																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
	By rank					By grade					Ash per cent	Fusion point				Sulphur	Caking				Sp gr	Storage	Handling	Pulverized																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
	By type	Class	Group	Classification	Size	Impurities	Deviation	Moisture per cent	Chemical composition	Initial temp		Soft temp	Fluid temp	Volatile per cent	Fixed carbon		Btu./lb	As sampled per cent	Forms	Phosphorus					Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering	Size stability	Friability	Grindability	Smoke, potential	Universal limitations																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

**Table 15-16. Coal Selection Chart for Gas and Coke Making<sup>1,2</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

	Classification					Specific chemical properties of coal										Specific physical properties**					General					Coke and by-products												
	By rank		By grade			Ash per cent	Fusion point				Sulphur			Caking	Sp gr	Storage	Handling	Pulverized																				
	By type	Class	Group	Classification	Size																	Impurities	Deviation	Moisture per cent	Chemical composition	Initial temp	Soft temp	Fluid temp	Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forma	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index
Reference notes <sup>2</sup>	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z														
Gas Making <sup>a</sup>																																						
Coal Gas:	b	b	b	b	c	b	a	c	b	c	b	c	a	b	b	a	c	—	c	b	b	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Horizontal retort	b	a	a	b	b	b	b	c	b	c	b	c	a	b	b	a	c	—	c	b	b	b	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Vertical retort	b	a	a	b	b	b	b	c	b	c	b	c	a	b	b	a	c	—	c	b	b	b	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
City water gas:	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Bituminous	b	—	c	a	b	b	c	b	c	b	c	b	c	b	a	—	c	c	c	c	b	a	b	a	—	—	—	—	—	—	—	—	—	—	—	—	—	
Anthracite	—	—	—	b	a	b	b	c	b	b	b	b	c	b	b	a	—	—	c	c	c	b	a	b	a	—	—	—	—	—	—	—	—	—	—	—	—	
Producer gas (from coal):	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Hot raw	b	b	b	c	b	b	b	c	b	c	b	c	b	c	b	c	c	c	c	c	c	a	b	c	c	—	—	—	—	—	—	—	—	—	—	—	—	
Clean	b	b	b	c	b	b	c	b	c	b	c	b	c	b	c	b	c	c	c	c	c	a	b	c	c	—	—	—	—	—	—	—	—	—	—	—	—	
High-temperature Coke Making																																						
Blast-furnace coke	b	a	b	c	c	b	a	b	b	a	—	c	—	b	b	a	c	a	c	b	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Foundry coke	b	a	b	c	c	b	a	b	b	a	b	c	b	b	b	b	a	c	a	c	b	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Domestic Coke	b	a	b	c	c	b	a	b	b	a	b	c	b	a	b	b	b	a	c	a	c	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Gas-making coke	b	a	b	c	c	c	b	a	b	a	b	b	a	b	a	b	a	c	—	c	c	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Industrial heating coke	b	a	b	c	c	c	b	c	a	b	b	a	a	b	a	b	a	c	—	c	c	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Chemical coke:	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Lime	b	a	b	c	c	c	a	b	c	b	c	b	a	c	a	c	a	c	—	c	a	a	a	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Carbon dioxide	b	a	a	c	c	b	a	c	b	b	—	b	a	c	a	c	a	b	a	c	c	a	a	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hydrogen	b	a	b	c	c	c	b	c	b	b	b	a	a	a	c	a	c	—	c	c	a	b	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Low-temperature Coke																																						
Domestic coke	b	b	b	c	c	b	a	c	a	b	c	b	b	c	a	b	a	—	c	c	c	a	c	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.<sup>3</sup> ASTM Specifications D166-24.<sup>4</sup> ASTM Specifications D17-16.<sup>5</sup> ASTM Specifications D166-24.

Table 15-17. Coal Selection Chart for Ceramic Products<sup>1, a</sup>

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

Reference notes <sup>a</sup> .....	Classification										Specific chemical properties of coal							Specific physical properties <sup>a,b</sup>					General																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	By type			By rank		By grade		Moisture per cent	Ash per cent	Fusion point			Sulphur	Caking			Sp gr	Storage	Handling	Pulverized																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
	Class	Group	Classification	Size	Impurities	Deviation	Chemical composition			Initial temp	Soft temp	Fluid temp		Volatile per cent	Fixed carbon	Btu/lb					As sampled per cent	Forms	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering	Size stability	Friability	Grindability	Smoke, potential	Universal limitations																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
c	d	e	f	g	h	i	j	k	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h

## Common Brick, Hollow Building Tile, Drain Tile, Face Brick, and Paving Brick

Clamp or scove (induced).	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Periodic downdraft:	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Induced	c	b	c	c	b	b	c	c	c	c	c	c	c	c	b	c	c	c	c	c	c	c	c	c	c
Forced	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Continuous, induced	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Tunnel, forced:	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Direct	c	b	b	b	b	c	b	c	c	c	c	c	c	c	b	c	c	c	c	c	c	c	c	c	c
Muffle ..	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c

## Refractories, Sewer Pipe, Pottery, and Grinding Wheels

Periodic downdraft:	c	b	c	c	b	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Induced	c	b	c	c	b	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Forced	c	b	c	c	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Periodic updraft:	c	b	c	c	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Induced	c	b	c	c	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Forced	c	b	c	c	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Continuous, induced	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Tunnel, forced:	c	b	b	b	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Direct	c	b	b	b	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Muffle	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c

## Terra Cotta

Muffle:	c	b	c	a	c	b	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Induced	c	b	c	a	c	b	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Forced ..	c	b	c	a	c	b	b	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c

## White Ware, Sanitary Ware, and Floor and Wall Tile

Periodic downdraft:	c	b	c	b	c	b	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Induced	c	b	c	b	c	b	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Forced	c	b	c	b	c	b	c	b	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Periodic updraft:	c	b	c	b	b	a	c	b	b	c	c	b	c	a	b	b	a	b	a	b	a	b	a	b	a
Induced	c	b	c	b	c	a	c	b	b	c	c	b	c	a	b	b	a	b	a	b	a	b	a	b	a
Forced	c	b	c	b	c	a	c	b	b	c	c	b	c	a	b	b	a	b	a	b	a	b	a	b	a
Tunnel, forced:	c	b	c	b	c	b	c	b	b	c	c	c	c	c	b	b	c	a	c	c	c	c	c	c	c
Direct	c	b	c	b	c	b	c	b	b	c	c	c	c	c	b	b	c	a	c	c	c	c	c	c	c
Muffle	c	b	c	b	c	b	c	b	b	c	c	c	c	c	b	b	c	a	c	c	c	c	c	c	c

<sup>1</sup> American Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

Table 15-18. Coal Selection Chart, Miscellaneous<sup>1,2</sup>

(Legend: a = very essential, b = more than ordinary importance, c = ordinary importance, — = not important. No entry = to be developed)

	Classification							Specific chemical properties of coal							Specific physical properties <sup>3,4</sup>							General															
	By rank			By grade				Ash per cent	Fusion point		Sulphur	Caking			Sp gr	Storage	Handling	Pulverized																			
	By type	Class	Group	Classification	Size	Impurities	Deviation		Moisture per cent	As sampled		Chemical composition	Initial temp	Soft temp					Fluid temp	Volatile per cent	Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering	Size stability	Friability	Grindability
Reference notes <sup>2</sup>	c	d	d	e	f	g	i	h	h	j	h	h	h	h	h	h	h	h	k	h	l	m	n	o	p	q	r	s	t	u	v	w	x	yy			
Cement Burning																																					
Rotary kilns, direct	c	b	—	—	c	c	c	b	c	c	c	—	—	a	—	a	b	b	b	—	—	—	—	—	—	—	—	c	c	—	—	c	—	—			
Lame Burning																																					
Rotary kilns:	c	b	c	c	b	c	c	c	b	—	b	a	—	b	a	c	—	b	c	—	—	—	—	—	—	—	b	b	b	c	b	—	—	—			
Producer gas	c	b	c	c	c	c	c	c	c	b	a	a	—	b	a	c	—	c	c	—	—	—	—	—	—	—	b	b	b	c	c	—	—	—			
Direct-fired	c	b	c	c	c	c	c	c	c	b	a	a	—	b	a	c	—	c	c	—	—	—	—	—	—	—	b	b	b	c	c	—	—	—			
Stationary kilns:	c	b	c	c	b	c	c	c	b	—	b	a	—	b	a	c	—	b	c	—	—	—	—	—	—	—	b	b	c	b	—	—	—	—			
Producer gas	c	b	c	c	c	c	c	c	c	—	c	a	—	b	a	c	—	c	c	—	—	—	—	—	—	—	b	b	c	b	—	—	—	—			
Direct-fired	c	b	c	c	c	c	c	c	c	—	c	a	—	b	a	c	—	c	c	—	—	—	—	—	—	—	b	b	c	b	—	—	—	—			
Locomotives																																					
Hand-fired:	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Passenger	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Freight	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Switch	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Stoker-fired:	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Passenger	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Freight	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Switch	c	b	c	c	b	b	b	c	b	b	c	b	b	b	c	b	b	—	—	—	—	—	—	—	—	—	a	b	b	b	—	b	—	—			
Smoke-restriction territory	c	b	c	c	b	b	b	c	b	b	c	b	c	a	a	b	b	—	—	c	—	—	—	—	—	—	a	b	b	b	—	a	—	—			
Metallurgical																																					
Smelting (direct with coal)	a	a	a	a	b	b	b	b	b	—	—	—	—	c	a	b	a	c	a	—	—	c	c	c	c	—	b	b	b	b	—	c	—	—			
Furnaces:					c	b	b	b	a	b	b	b	b	c	b	a	c	c	b	—	—	—	—	—	—	—	b	b	c	b	b	—	b	—			
Malleable					c	b	b	b	a	b	a	a	a	b	c	b	a	c	c	b	—	—	—	—	—	—	b	b	c	b	b	—	b	—			
Open-hearth					c	b	b	b	a	b	a	a	a	b	c	b	a	c	c	b	—	—	—	—	—	—	b	b	c	b	b	—	b	—			
Pulverized <sup>3,4,5</sup>					c	b	b	b	a	b	a	a	a	b	c	b	a	c	c	b	b	b	b	—	—	—	b	b	c	b	b	—	b	—			
Smelting					c	b	b	c	b	b	—	—	—	—	—	a	c	a	c	c	b	b	b	—	—	c	c	c	c	c	—	—	—				
Miscellaneous					c	c	c	c	c	—	—	—	—	—	b	—	a	c	a	c	—	—	—	—	—	—	c	c	c	c	c	—	—	—			
Recarburizing:					c	c	c	a	b	b	—	—	—	—	a	a	c	a	c	—	—	—	—	—	—	—	b	b	b	c	b	—	—	—			
In open-hearth					c	c	c	a	b	b	—	—	—	—	a	a	b	b	c	—	—	—	—	—	—	—	b	b	b	c	b	—	—	—			
General					c	c	c	b	b	c	—	a	—	a	b	b	c	b	c	—	—	—	—	—	—	—	b	b	b	c	b	—	—	—			
Foundry Facings																																					
	a	a	a	c	b	a	b	a	a	—	—	c	—	a	a	—	a	a	c	a	—	—	—	—	—	—	a	c	c	—	—	a	—	a			
Colloidal																																					
	b	b	b	b	b	a	a	b	a	—	c	b	c	b	b	b	b	b	b	—	—	—	—	—	—	b	—	—	b	—	—	a	—	—			
Industrial Processes (Anthracite)																																					
Reduction	...	...	...	a	a	—	a	b	—	b	—	—	—	—	—	—	a	b	a	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—			
Filtration	...	...	...	a	a	—	a	b	—	b	—	—	—	—	—	—	—	a	b	a	—	—	—	—	—	b	—	—	—	a	a	a	—	—			

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.



**Table 15-19. Coal Selection Chart for Domestic, Cargo, and Bunker<sup>1,2</sup>**

(Legend: a = very essential. b = more than ordinary importance. c = ordinary importance.  
— = not important. No entry = to be developed)

	Classification							Specific chemical properties of coal										Specific physical properties**						General												
	By rank			By grade				Ash per cent	Fusion point			Sulphur	Caking			Sp gr	Storage	Handling	Pulverized																	
	By type	Class	Group	Classification	Size	Impurities	Deviation		Moisture per cent	Chemical composition	Initial temp		Soft temp	Fluid temp	Volatile per cent					Fixed carbon	Btu/lb	As sampled per cent	Forms	Phosphorus	Coke button	Agglutinating	Expansion	Specific volume index	Of lump	Bulk density	Plasticity	Spontaneous combustion	Weathering	Size stability	Fraility	Grindability
Reference notes <sup>2</sup>	c	d	d	e	f	g	i	h	h	j	h	h	h	h	h	h	h	k	h	l	m	n	o	p	q	r	s	t	u	v	w	z	yy			
Domestic Anthracite																																				
Hand-fired	c	—	—	b	b	b	c	c	c	c	c	c	c	b	b	c	c	—	—	—	—	—	—	c	c	—	—	—	—	b	b	—	—			
Overfeed stoker	c	—	—	e	b	b	c	c	c	c	b	b	b	c	b	b	c	—	—	—	—	—	—	c	c	—	—	—	—	c	c	—	—			
Magazine	c	—	—	b	a	b	c	c	c	c	b	b	b	b	b	b	c	—	—	—	—	—	—	c	c	—	—	—	—	c	c	—	—			
Domestic Bituminous <sup>bbbb</sup>																																				
Hand-fired	c	—	c	c	b	b	c	c	c	c	—	—	b	b	b	b	c	c	—	—	—	c	—	—	c	c	c	b	b	b	b	a	a	—		
Overfeed stoker	c	—	c	c	b	b	c	c	c	c	—	—	c	b	b	b	c	c	—	—	—	c	—	—	c	c	b	b	b	b	c	a	a	—		
Underfeed stoker	c	—	c	c	b	b	a	c	b	c	c	b	b	b	b	b	c	c	—	—	—	c	—	—	c	b	b	b	b	b	c	a	a	—		
Domestic Fireplaces																																				
Anthracite	c	—	—	b	b	c	c	c	b	c	—	—	b	c	b	c	c	—	—	—	—	—	—	c	c	—	—	—	—	b	b	—	c	—		
Bituminous	c	—	c	c	b	c	c	c	c	c	—	c	c	c	c	c	c	—	—	—	—	—	—	c	c	—	c	—	b	b	b	—	a	—		
Briquetting																																				
Anthracite	c	—	—	b	b	b	a	b	a	c	c	c	c	c	b	c	c	—	—	—	—	—	—	c	c	—	—	—	—	—	c	c	—	—		
Bituminous	c	—	c	c	b	b	b	b	b	c	c	c	c	b	b	c	c	—	—	c	—	—	b	b	c	c	b	—	—	—	—	—	a	—		
Bunker <sup>b</sup>																																				
Export	c	b	c	a	b	a	b	a	a	c	a	a	a	b	a	a	c	—	c	c	c	c	—	—	—	a	b	c	c	c	—	b	—	—		
Lake	c	b	c	b	b	b	b	b	b	c	b	a	b	b	b	b	c	—	—	—	—	—	—	—	—	a	c	c	c	c	—	c	—	—		
Cargo <sup>cc</sup>																																				
Export	a	a	a	a	b	b	b	b	a	a	c	a	b	a	a	a	c	—	b	b	b	b	b	—	a	b	a	a	a	b	b	—	—	—		
Lake	c	b	c	b	b	b	b	b	b	c	a	b	b	b	b	b	—	—	—	—	—	—	—	—	a	c	a	a	a	—	—	—	—			
Dock storage	c	b	c	b	b	b	b	b	b	c	a	b	b	b	b	b	—	—	—	—	—	—	—	—	a	c	a	a	a	—	—	—	—			

<sup>1</sup> National Association of Purchasing Agents.<sup>2</sup> See Detailed Reference Notes on pp. 516-517.

Bituminous, Subbituminous, and Lignite: In accordance with method developed by Subcommittee VII of the Technical Committee on Coal Classification.

Powdered Coal: In accordance with ASTM Standard D197-30.

g. Anthracite. Impurities consist of inherent ash, approximately 8 to 9 per cent, much of which cannot be physically removed. Practically all the slate and real bone are now removed mechanically at most large mines.

Bituminous, Subbituminous, and Lignite. Extraneous matter possible to remove by commercial coal cleaning (as being developed by the ASA Sectional Committee on Clean Bituminous Coal).

h. According to ASTM Standard D271-33 for Proximate Analysis, etc. (temperature interval between points of ash fusion may develop to be a factor in coal selection).

i. Deviation of individual shipments from the average. See 1933 ASTM "Manual on Presentation of Data."

j. Analysis of ash in accordance with U.S. Steel Corp., "Methods for the Sampling and Analysis of Coal, Coke and By-products," 3d ed, pp. 93-104. Evidence has been developed to support the fact that, with ultimate analysis of ash, the fusing temperature can be predetermined and controlled.

jj. For pure white ware, the volatile sulphur is of prime importance, since it is that part of the sulphur which comes into direct contact.

k. Pyritic, sulphate, and organic sulphur as percentage of total sulphur, according to U.S. Bur. Mines Tech Paper 254.

kk. The physical characteristics of the ash, especially fly ash, may affect coal selection.

l. According to Canada Department of Mines method, *Trans. AIME*, Coal Division, 1934, pp. 255-265.

m. According to method described in *ASTM, Proc.*, vol. 33, Part II, pp. 754-757.

n. No practical method of determination for general use has yet been developed.

nn. A test was recently developed by Alteri and described in a paper read before the AGA in 1935.

o. According to method described in *Can. Dept. Mines Resources Pub.* 725-2.

p. According to ASTM D167-24.

q. According to ASTM D292-29 for lump coal, and ASTM D291-29 for coal under 1½ in. in size.

r. By Bureau of Mines plastometer method as described by J. D. DAVIS, The Plastometer; A New Instrument for Measuring Plastic Properties of Coal, *Ind. Eng. Chem., Anal. Ed.*, vol. 3, p. 43, 1931.

s. The behavior of a coal with reference to spontaneous combustion depends on its rank, size, friability, and sulphur content, together with the method of laying down in the storage pile, evenness of coal particles, moisture content of the fines, and the access of currents of air through the coal during its storage. Hence relative importance of storage properties in respect to spontaneous combustion will depend on storage facilities whether (1) storage indoors or under cover to not more than, say, 10 ft, or (2) storage outdoors in piles as high as 40 ft.

t. According to slacking-index method, U.S. Bur. Mines Repts. Invent. 3055 modified by using a standard humidity of 30 to 35 per cent.

u. By ASTM Coke Shatter Test Method D141-23, as it may be modified for coal by ASTM Committee D-5.

v. By small-jar tumbler test described by J. H. H. NICOLLS, Friability Test of Various Fuels Sold in Canada, *Can. Dept. Mines, Resources Mines Branch, Investigations of Fuels and Fuel Testing, Bull.* 644, 1924, pp. 20-35, as it may be modified by ASTM Committee D-5.

w. By the ball-mill method or by the Hardgrove machine method as described in *ASTM, Proc.*, Part I, 1935.

x. Measured by percentage of primary tar as determined by the Fischer low-temperature assay described by W. A. Selvig and W. H. Ode, Evaluation of Laboratory Assay Test for Determination of Gas, Coke and By-products of Coal, *Ind. Eng. Chem.* Volatile-matter restrictions by cities.

y. According to U.S. Steel Corp., "Methods for the Sampling and Analysis of Coal, Coke and By-Products," 3d ed, pp. 130-143. The application of factors for conversion refer to *Ind. Eng. Chem., Anal. Ed.*, vol. 7, 1935, paper by W. A. SELVIG, U.S. Bureau of Mines, Pittsburgh, Pa. An alternate method is prescribed by the Bureau of Mines and AGA using the assay furnace.

yy. Any actual numerical limits of factors accepted universally for each specific use.

z. According to ASTM Standard D167-24.

zz. Factors affecting loading, transit, unloading, and not related to ultimate use.

**Factors in the Selection of Anthracite.** Table 15-20 shows somewhat more specific data than those of the foregoing coal selection charts as applied to anthracite alone. These are based on the figures that were submitted to the committee by Anthracite Institute Laboratory at the time of the preparation of the chart, with, however, some basic changes by the authors to conform to current practices.

## COAL SPECIFICATIONS<sup>1</sup>

(Items for Inclusion in Coal Specifications and Significance)

For actual purchasing purposes, coal specifications may include such factors as the following:

**1. Size of Coal.** Specify size range acceptable. Specify smallest size that will give acceptable performance.

<sup>1</sup> Coal Bureau, Upper Monongahela Valley Association, *Reference Bull.* 3, New York.

**2. Definition.** Require bidders to give size, proximate analysis, friability, and grindability on coal offered.

**3. Quality or Grade.** Include as many of the following as may materially affect the use or value of coal in your plant. Specify analytical range acceptable (per cent to per cent) for each item included.

- |                       |  |
|-----------------------|--|
| a. Moisture as loaded | e. Sulphur                                       |
| b. Volatile matter    | f. Ash-softening temperature, degrees Fahrenheit |
| c. Fixed carbon       | g. Btu as loaded (minimum acceptable)            |
| d. Ash                |  |

**4. The ultimate in utilization flexibility** is provided when:

- The buyer specifies minimum Btu per pound (as loaded) acceptable.
- The bidder specifies the delivered cost per million Btu.

**Table 15-20. Factors in the Selection of Anthracite for Various Equipment**

Equipment	Water-gas	Hand-fired (steam)	Traveling grate	Hand-fired (domestic)	Underfeed stoker	Magazine feed
Preferred coal sizes <sup>a</sup>	Broken, egg	Buckwheat, rice	Barley, No. 4 buckwheat	Egg, stove, chestnut	Buckwheat, rice	Buckwheat
Moisture, max per cent.....	5 0	5 0	5 0	5 0	5 0	5 0
Ash, max per cent .	11 0	13 0	15 0	11 0	13 0	13 0 <sup>b</sup>
Ash deviation, per cent	0 5	2 0	2 0	1 0	2 0	1 5
Volatile, per cent...	3-8	3-9 5	3 5-8	3-8	3 5-9	3 5-8
Btu, avg . . . .	13,150	12,500	12,300	13,000	12,500	12,750
Softening temp, deg F	2600-3000	2300-3000	2750-3000	2600-3000	2750-3000	2750-3000
Sulphur, per cent	0-1 5	0-1 5	0-1 5	0-1 5	0-1 5	0-1 5
Caking . . . . .	None	None	None	None	None	None
Spontaneous combustion . . . . .	None	None	None	None	None	None
Smoke . . . . .	None	None	None	None	None	None
Weathering . . . . .	Slight	Slight	Slight	Slight	Slight	Slight
Sp gr (lump) . . . .	1 58 <sup>c</sup>	1 58 <sup>c</sup>	1 58 <sup>c</sup>	1 58 <sup>c</sup>	1 58 <sup>c</sup>	1 58 <sup>c</sup>
Sp gr (bulk), lb/cu ft..	55	55	55	55	55	55
Size stability . . . .	Data not available					
Lack of skill . . . .	As anthracite should not be disturbed during combustion, skill is relatively unimportant					

<sup>a</sup> For hand-firing, coal size should be in proportion to the depth and diameter of the furnace (domestic); for other equipment, the preferred size is usually shown first

<sup>b</sup> While 13.0 is the industry's limit of ash for buckwheat, magazine boilers perform best with low-ash coals and with coals having a high coefficient of ash shrinkage.

<sup>c</sup> Average of 104 samples from all parts of the region.

### Common Errors in Buying Coal on Specifications<sup>1</sup>

While coal specifications have the obvious advantages of protecting the purchaser against poorly adapted or improperly prepared coal, extreme care should be taken to see that the very specifications designed to protect do not act in reverse to cut the plant off from desirable sources of supply because of unduly rigid provisions. Hardships imposed upon the purveyor in connection with finding a coal to meet rigid requirements are usually reflected in the price, often out of proportion to the advantages gained.

In general, unless the specifications can be drawn up and continuously supervised by a competent engineer thoroughly familiar with all plant and coal-market conditions, the plant will be better advised to purchase in the open market.

Many plants have been wisely designed to use a wide range of coals. In spite of

<sup>1</sup> Coal Bureau, Upper Monongahela Valley Association, *Reference Bull.* 3, New York.

this, in many cases, specifications have been issued so limiting the selective range as to exclude many desirable potential bidders.

The most common errors are those involving volatile content, ash-fusion temperature, and grindability index of the coal.

**Spreader stokers** characteristically use a very wide range of coals with satisfactory results even with high volatiles, high sulphur, medium Btu, and low ash fusion. Liberal specifications will therefore vastly expand the number of coals available to the plant.

Most modern **pulverizer installations**, unlike earlier ones, have capacities to permit the use of coals having a low or medium grindability index; *e.g.*, 50 to 70 (Hardgrove scale). However, old-fashioned specifications are frequently issued for these calling for high grindability indexes. In other instances, high-volatile coals would be advantageous for fast ignition, such as in undersized furnaces, yet the coal specifications often call for coal of extremely low volatility.

In the case of underfeed stokers, errors in coal specifications, because of over stringency, are noticeably fewer, and this for the reason that many underfeed-stoker installations are conversions from oil or hand-firing, with tight furnaces and small grates. When affected by such factors, the coal-selectivity range is so narrowed that this should be reflected in the specifications. In these cases, specifications can be drawn to protect against troublesome clinker, either by calling for double-screened coal (*i.e.*, fines removed), which will result in greater fuel-bed porosity and reduced fuel-bed temperatures, or by specifying higher ash-fusion temperature to meet the excessive fuel-bed temperatures. However, when conditions are normal and maximum burning rates on underfeed stokers are on the order of 30 to 35 psf of grate area, coals having a minimum ash-softening temperature as low as 2100°F can be specified.

#### COST OF FUEL AND ELECTRICITY IN VARIOUS INDUSTRIES<sup>1</sup>

Table 15-21 shows the cost of fuel and electricity of 254 industries as represented by 146,731 plants and establishments. Costs are shown both as total dollars spent per year by these plants (\$1,260,626,000 in 1945), and as per cent of the value of the products manufactured.

Fuel costs ranged from 0.1 per cent or less of the value of the manufactured products (coats and suits, cigarettes, cigars, lamp shades, men's suits, and cosmetics) to 26.4 per cent (blast-furnace products), with a weighted average of 1.72 per cent.

Electricity costs ranged from 0.1 per cent or less of the value of the manufactured products (cigarettes, secondary smelting of rare metals) to 12.3 per cent (manufactured ice), with a weighted average of 1.01 per cent.

Thus the total fuel and electricity cost averaged 2.73 per cent of the value of the manufactured products, and averaged \$8,591 per plant.

The effect of an increase in fuel or power costs, or conversely the value of savings, in terms of the corresponding effect on the cost of the finished product, may be estimated from these data. Thus, if fuel is 1 per cent of the value of the finished product, an increase in 10 per cent of the fuel price will increase the product cost by 10 per cent of 1 per cent or 0.1 per cent. These data are also of value in determining whether a particular plant is in line with its industry.

<sup>1</sup> Sworn testimony of the National Coal Association, before the Federal Power Commission, Natural Gas Investigation, Docket G-580, 1946.

Table 15-21. Relation between Fuel Cost and Value of Manufactured Products<sup>1</sup>

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	Electricity	Total
Abrasive wheels, stones, paper, cloth, and related products . . . . .	124	1,454	1 0	1.0	2 0
Agricultural machinery, except tractors . . . . .	317	2,750	1 1	0 5	1 6
Aircraft and parts, including aircraft engines . . . . .	125	1,857	0 2	0 5	0.7
Alloying, and rolling and drawing of nonferrous metals except aluminum . . . . .	188	10,270	1.2	1.1	2 3
Aluminum products (including rolling, drawing, and extruding) . . . . .	162	3,211	1.0	0.9	1 9
Aluminum ware, kitchen, hospital, and household (except electrical) . . . . .	32	546	0 6	0 9	1 5
Artificial leather and oilcloth . . . . .	36	717	1.1	0 6	1 7
Asbestos products (except steam packing, pipe and boiler covering) . . . . .	79	1,625	1 5	1 2	2 7
Automobile stampings . . . . .	90	784	0 5	1 1	1 6
Baking powder, yeast, and other leavening compounds . . . . .	47	921	1 8	1 1	2 9
Batteries, storage and primary (dry and wet) . . . . .	221	2,484	0 8	1 3	2 1
Beet sugar . . . . .	85	5,707	4 1	0 2	4 3
Biscuit, crackers, and pretzels . . . . .	356	2,584	0.9	0 4	1 3
Blast-furnace products . . . . .	81	146,945	26.4	0 3	26 7
Bolts, nuts, washers, and rivets (not made in rolling mills) . . . . .	155	1,868	1 1	1 1	2 2
Bookbinding and related industries . . . . .	1,133	1,054	0 3	0 7	1 0
Books; printing without publishing . . . . .	690	1,144	0.3	1 0	1 3
Boot and shoe cut stock and findings . . . . .	520	865	0 2	0 4	0 6
Bread and other bakery products (except biscuit, crackers, and pretzels) . . . . .	18,043	27,438	1 3	0 9	2 2
Brick and hollow structural tile . . . . .	800	15,385	16 2	3 5	19 7
Brushes . . . . .	245	382	0 3	0 5	0 8
Candy and other confectionery products . . . . .	1,252	3,560	0 6	0 6	1 2
Cane-sugar refining . . . . .	27	4,540	1 1	0 03	1 13
Canned and dried fruits, vegetables, and soups . . . . .	2,007	5,826	0 7	0 3	1 0
Canned fish, crustacea, and mollusks . . . . .	214	595	0 6	0.3	0 9
Carbon products for the electrical industry, carbons and graphite . . . . .	31	1,301	3 0	4 1	7.1
Carpets and rugs, wool . . . . .	43	1,910	1 0	0 4	1 4
Cars and car equipment; railroad, street, and rapid transit . . . . .	143	2,373	0 9	0 5	1 4
Caskets, coffins, and other morticians' goods . . . . .	599	852	0 6	0 6	1 2
Cast-iron pipes and fittings . . . . .	74	3,221	3 8	1 2	5 0
Cement . . . . .	160	34,073	12 5	5 1	17 6
Cheese . . . . .	2,082	2,046	1 3	0 6	1 9
Chemicals, not elsewhere classified . . . . .	543	48,318	3 8	2 0	5 8
China firing and decorating (for the trade) . . . . .	24	35	1 2	0 3	1 5
Chocolate and cocoa products . . . . .	39	1,466	0 7	0 7	1 4
Cigarettes . . . . .	35	1,069	0 07	0 03	0 1
Cigars . . . . .	598	708	0 1	0 3	0 4
Clay products (except pottery) not elsewhere classified . . . . .	99	691	13 3	2 2	15 5
Clay refractories, including clay-refractory cement . . . . .	165	4,404	8 6	1.9	10 5
Cleaning and polishing preparations, blackings and dressings . . . . .	637	604	0 3	0.3	0 6
Clocks, watches, materials, and parts (except watch cases) . . . . .	74	506	0 3	0 3	0 6
Cloth sponging and miscellaneous special finishing . . . . .	112	365	1 0	0 5	1 5
Coal-tar products, crude and intermediate . . . . .	49	1,440	2 9	0 5	3 4
Coated and glazed paper . . . . .	140	1,137	0 6	0 7	1 3
Coats, suits, and skirts (except fur coats) made in contract factories . . . . .	846	452	0 4	1 0	1 4

<sup>1</sup> National Coal Association, Sworn testimony before Federal Power Commission hearing on general oil pipe-line policy.

<sup>a</sup> Total fuel cost and purchased electric energy in thousands of dollars.

**Table 15-21. Relation between Fuel Cost and Value of Manufactured Products.<sup>1</sup>**  
(Continued)

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	Elec- tricity	Total
Coats, suits, and skirts (except fur coats) made in inside factories. . . . .	1,120	767	0.04	0.24	0.28
Cold-rolled steel sheets and strip and cold-finished steel bars . . . . .	43	1,560	0.9	1.3	2.2
Colors and pigments. . . . .	89	3,218	2.6	1.2	3.8
Communication equipment . . . . .	227	1,574	0.5	0.3	0.8
Concrete products . . . . .	2,040	1,916	0.7	0.8	1.5
Condensed and evaporated milk . . . . .	562	5,782	2.2	0.6	2.8
Construction machinery (except mining and oil-field machinery) . . . . .	199	2,007	0.7	0.7	1.4
Converted paper products not elsewhere classified . . . . .	384	1,365	0.4	0.5	0.9
Cooking and other edible fats and oils, not elsewhere classified . . . . .	56	2,069	0.7	0.4	1.1
Cordage and twine . . . . .	116	1,378	0.5	1.9	2.4
Cork products . . . . .	35	441	1.6	0.9	2.5
Corn sirup, corn sugar, corn oil, and starch . . . . .	35	3,254	2.6	0.2	2.8
Cotton broad woven goods. . . . .	661	31,566	1.0	2.6	3.6
Cotton narrow fabrics . . . . .	163	993	0.9	1.1	2.0
Cottonseed oil, cake, meal, and linters . . . . .	447	3,962	1.0	1.3	2.3
Cotton thread . . . . .	75	1,288	1.1	1.4	2.5
Cotton yarn . . . . .	349	7,975	0.4	3.6	4.0
Creamery butter . . . . .	3,506	7,966	0.9	0.7	1.6
Cutlery (except aluminum, silver, and plated) and edge tools . . . . .	266	1,179	0.9	1.1	2.0
Dental equipment and supplies . . . . .	131	265	0.4	0.4	0.8
Doors, window sash, frames, molding, and trim (made of metal) . . . . .	205	535	0.4	0.7	1.1
Drugs and medicines (including drug grinding) . . . . .	1,094	2,280	0.4	0.3	0.7
Dyeing and finishing cotton, rayon, silk, and linen textiles . . . . .	468	12,258	3.7	0.8	4.5
Dyeing and finishing woolen and worsted . . . . .	63	968	2.2	0.4	2.6
Electric appliances . . . . .	138	1,604	0.4	0.7	1.1
Electric lamps . . . . .	55	1,005	0.4	0.7	1.1
Electrical products not elsewhere classified . . . . .	175	656	0.6	1.1	1.7
Electroplating, plating and polishing . . . . .	643	1,322	1.3	3.4	4.7
Elevators, escalators, and conveyors . . . . .	183	763	0.5	0.7	1.2
Embroideries; Schiffli-machine products . . . . .	398	204	0.5	1.0	1.5
Enameled-iron sanitary ware and other plumbers' supplies . . . . .	358	4,013	2.2	1.0	3.2
Enameling, japanning, and lacquering . . . . .	80	402	3.4	2.3	5.7
Engraving on metal (except for printing purposes) . . . . .	94	82	0.6	0.8	1.4
Explosives . . . . .	80	1,681	1.4	0.9	2.3
Fabricated plastic products, not elsewhere classified . . . . .	216	1,622	1.1	1.2	2.3
Fabricated structural steel and ornamental metalwork . . . . .	1,138	2,982	0.4	0.7	1.1
Felt goods, wool, hair, and jute (except woven felts and hats) . . . . .	37	601	1.5	1.0	2.5
Fertilizers. . . . .	764	2,286	0.3	0.9	1.2
Fiber cans, tubes, and similar products . . . . .	116	712	1.4	0.7	2.1
Files . . . . .	22	321	2.0	0.8	2.8
Firearms . . . . .	23	436	1.4	1.1	2.5
Fish and other marine oils, cake and meal . . . . .	76	453	2.7	0.6	3.3
Flavoring extracts and flavoring sirups . . . . .	477	493	0.2	0.2	0.4
Floor and wall tile (except quarry tile) . . . . .	49	1,181	5.2	1.5	6.7
Flour and other grain-mill products . . . . .	2,143	8,483	0.3	1.0	1.3
Food preparations not elsewhere classified . . . . .	1,007	1,668	0.6	0.4	1.0
Food products machinery . . . . .	379	1,086	0.5	0.7	1.2
Footwear (except rubber). . . . .	1,070	4,012	0.2	0.3	0.5
Forgings, iron and steel. . . . .	207	5,183	3.6	1.3	4.9
Fuel briquettes. . . . .	32	250	1.7	3.0	4.7

Table 15-21. Relation between Fuel Cost and Value of Manufactured Products.<sup>1</sup>  
(Continued)

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	electricity	Total
General commercial (job) printing..	9,595	6,620	0 3	1 0	1 3
Generating, distribution, and industrial apparatus	491	5,998	0 7	0 6	1 3
Glass containers . . . . .	77	12,102	5 9	1 7	7 6
Glue and gelatin . . . . .	80	1,766	4 6	0 5	5 1
Gray iron and semisteel castings . . . . .	1,161	10,978	3 6	1 6	5 2
Grease and tallow (except lubricating greases)	310	2,000	2 3	1 1	3 4
Gum naval stores (processing but not gathering or warehousing) . . . . .	755	194	1 04	0 06	1 1
Gypsum products . . . . .	68	2,727	3 1	2 8	5 9
Hardware not elsewhere classified . . . . .	434	2,791	1 0	0 8	1 8
Hardwood distillation and charcoal manufacture	43	771	10 3	1 0	11 3
Hat bodies and hats, fur felt. . . . .	43	810	1 6	0 5	2 1
Hatters' fur. . . . .	37	158	0 9	0 5	1 4
Hosiery, full fashioned.....	499	3,191	0 4	0 7	1 1
Hosiery, seamless . . . . .	433	1,739	0 6	0 6	1 2
Hotel china . . . . .	17	504	4 5	0 9	5 4
Household furniture, except upholstered	1,592	4,729	0 6	0 8	1 4
Ice, manufactured . . . . .	3,975	19,763	2 9	12 3	15 2
Ice cream and ices. . . . .	2,734	7,221	0 6	1 9	2 5
Industrial machinery not elsewhere classified	579	2,261	0 6	1 0	1 6
Insecticides, fungicides, and related chemicals	774	916	0 5	0 4	0 9
Insulated wire and cable . . . . .	79	1,846	0 7	0 8	1 5
Internal-combustion engines. . . . .	74	1,425	1 0	0 3	1 3
Jewelry (precious metals) . . . . .	886	360	0 2	0 3	0 5
Knitted cloth . . . . .	229	1,277	1 1	0 8	1 9
Knitted outerwear (except knit gloves)	476	626	0 2	0 4	0 6
Knitted underwear.....	199	1,410	0 7	0 5	1 2
Lace goods . . . . .	63	430	1 4	0 4	1 8
Lamp shades . . . . .	128	42	0 1	0 4	0 5
Laundry equipment, domestic . . . . .	42	653	0 5	0 6	1 1
Leather: tanned, curried, and finished; contract factories	111	682	2 7	1 4	4 1
Leather: tanned, curried, and finished; regular factories or jobbers. . . . .	335	5,008	1 1	0 4	1 5
Lighting fixtures.. . . .	568	1,626	0 5	0 8	1 3
Lime. . . . .	269	6,477	13 6	3 9	17 5
Linoleum and other hard-surface floor coverings, not elsewhere classified . . . . .	17	1,361	1 1	0 8	1 9
Linseed oil, cake, and meal . . . . .	25	777	0 6	0 5	1 1
Liquors, distilled . . . . .	135	2,290	3 4	0 7	4 1
Lithographing and photolithographing. . . . .	749	1,696	0 3	0 8	1 1
Lubricating oils and greases, not made in petroleum refineries . . . . .	232	664	0 9	0 4	1 3
Macaroni, spaghetti, vermicelli, and noodles	328	1,100	0 7	1 7	2 4
Machine tools . . . . .	200	2,618	0 5	0 7	1 2
Machine-shop products, not elsewhere classified	2,125	7,017	0 9	1 0	1 9
Malleable-iron castings.....	83	3,804	5 2	1 9	7 1
Malt. . . . .	52	1,974	2 3	1 1	3 4
Malt liquors . . . . .	605	9,690	1 3	0 5	1 8
Matches . . . . .	28	429	1 2	0 5	1 7
Meat packing, wholesale. . . . .	1,478	17,590	0 4	0 3	0 7
Mechanical power-transmission equipment . . . . .	218	3,163	0 7	1 2	1 9
Men's shirts (except work), collars and nightwear, jobbers . . . . .	449	873	0 2	0 3	0 5
Men's suits, coats, and overcoats (except work), contract factories.....	1,078	768	0 3	0 9	1 2
Men's suits, coats, and overcoats (except work), jobbers	1,371	1,735	0 1	0 2	0 3
Metalworking machinery accessories, metal-cutting tools, etc.....	954	2,149	0 5	1 2	1 7
Metalworking machinery and equipment, not elsewhere classified.....	178	1,418	0 6	0 8	1 4

**Table 15-21. Relation between Fuel Cost and Value of Manufactured Products.<sup>1</sup>**  
(Continued)

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	Electricity	Total
Mineral wool . . . . .	58	823	8 1	1 9	10 0
Minerals and earths, ground or otherwise treated . . . . .	237	2,254	2 5	3 3	5 8
Monuments, tombstones, cut-stone and stone products . . . . .	1,244	2,780	0 7	3 0	3 7
Motor vehicles, bodies, parts, and accessories . . . . .	1,054	35,394	0 5	0 4	0 9
Motorcycles, bicycles, and parts . . . . .	36	581	0 7	0 7	1 4
Needles, pins, hooks and eyes, and slide and snap fasteners . . . . .	58	453	0 5	0 7	1 2
Newspapers: publishing and printing . . . . .	6,878	9,857	0 3	0 8	1 1
Nonalcoholic beverages . . . . .	4,504	4,134	0 4	0 7	1 1
Nonclay refractories . . . . .	46	2,591	7 9	1 7	9 6
Nonferrous-metal foundries (except aluminum) . . . . .	600	1,572	1 8	1 0	2 8
Nonferrous-metal products not elsewhere classified . . . . .	438	2,842	0 9	1 1	2 0
Office furniture . . . . .	152	808	0 8	0 7	1 5
Office and store machines not elsewhere classified . . . . .	123	1,253	0 4	0 4	0 8
Oil-field machinery and tools . . . . .	223	1,530	0 6	1 1	1 7
Oleomargarine, not made in meat-packing establishments . . . . .	18	267	0 4	0 4	0 8
Ophthalmic goods: lenses and fittings . . . . .	91	619	0 8	0 6	1 4
Oven coke and coke-oven by-products . . . . .	83	11,226	2 6	0 7	3 3
Paints, varnishes, and lacquers . . . . .	1,166	3,990	0 4	0 5	0 9
Paper and paperboard mills . . . . .	638	58,894	4 7	1 6	6 3
Paperboard containers and boxes not elsewhere classified . . . . .	1,338	3,525	0 4	0 5	0 9
Partitions, shelving, cabinet work, office and store fixtures . . . . .	716	901	0 4	0 8	1 2
Paving blocks, asphalt, creosoted wood, and composition . . . . .	231	1,147	2 5	1 0	3 5
Pencils (except mechanical) and crayons . . . . .	40	293	1 1	0 7	1 8
Perfumes, cosmetics, and other toilet preparations . . . . .	539	465	0 1	0 2	0 3
Periodicals: publishing and printing . . . . .	600	1,479	0 3	0 4	0 7
Petroleum refining . . . . .	485	69,383	2 4	0 4	2 8
Pianos . . . . .	35	308	1 0	0 5	1 5
Pickled fruits, vegetables, vegetable sauces, and seasonings . . . . .	377	731	0 6	0 4	1 0
Planing mills not operated in conjunction with sawmills . . . . .	3,076	4,234	0 3	1 0	1 3
Plastic materials . . . . .	38	2,050	1 8	0 8	2 6
Porcelain electrical supplies . . . . .	42	912	3 2	1 2	4 4
Pottery products not elsewhere classified . . . . .	151	996	4 6	1 4	6 0
Poultry dressing and packing, wholesale . . . . .	765	898	0 2	0 4	0 6
Power boilers and associated products . . . . .	448	2,458	0 7	1 0	1 7
Prepared feeds (including mineral) for animals and fowls . . . . .	1,383	4,145	0 3	0 7	1 0
Primary smelting and refining nonferrous metals . . . . .	63	26,127	1 5	1 2	2 7
Printing-trades machinery and equipment . . . . .	231	749	0 6	0 8	1 4
Processed waste and recovered wool fibers, regular factories . . . . .	126	559	0 8	1 0	1 8
Professional and scientific instruments (except surgical and dental) . . . . .	218	476	0 3	0 5	0 8
Public-building furniture . . . . .	106	373	0 7	0 7	1 4
Pulp mills . . . . .	194	16,921	5 0	2 4	7 4
Pumping equipment and air compressors . . . . .	337	1,794	0 8	0 6	1 4
Radios, radio tubes, and phonographs . . . . .	224	1,841	0 3	0 4	0 7
Rayon and allied products . . . . .	30	7,114	2 4	0 5	2 9
Rayon broad woven goods, regular factories . . . . .	196	4,548	0 3	1 3	1 6
Rayon yarn and thread, spun or thrown, regular factories . . . . .	52	639	0 6	1 8	2 4
Refrigerators and complete air-conditioning units . . . . .	309	3,559	0 6	0 7	1 3
Roofing, built-up and roll; asphalt shingles (except paint) . . . . .	129	1,821	1 2	0 5	1 7
Rubber boots and shoes (including rubber-soled shoes) . . . . .	13	1,014	0 8	1 2	2 0
Rubber products, not elsewhere classified . . . . .	519	7,300	1 2	1 6	2 8



**Table 15-21. Relation between Fuel Cost and Value of Manufactured Products.<sup>1</sup>**  
(Continued)

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	Electricity	Total
Salt .. . . .	40	2,230	7.6	0.5	8.1
Sausages, prepared meats, etc., not made in packing houses....	1,067	2,268	0.4	0.7	1.1
Sawmills, veneer mills, and cooperage-stock mills ..	7,391	7,664	0.6	0.5	1.1
Screw-machine products and wood screws ..	345	1,715	0.6	1.4	2.0
Secondary smelting and refining, gold, silver, and platinum .....	66	257	0.2	0.1	0.3
Secondary smelting and refining of nonferrous metals	108	1,398	1.3	0.4	1.7
Sewer pipe and kindred products .. . . .	65	2,843	14.4	1.1	15.5
Sewing machines, domestic and industrial	39	514	1.0	0.7	1.7
Sheet-metal work not specifically classified	1,262	1,217	0.4	0.5	0.9
Shipbuilding and repairing.	406	4,138	0.5	0.8	1.3
Signs, advertising displays, and advertising novelties..	1,386	1,031	0.5	0.7	1.2
Silk broad woven goods, regular factories or jobbers...	82	663	0.7	1.2	1.9
Silk throwing and spinning, contract factories	78	1,018	0.7	5.3	6.0
Silk yarn and thread, spun or thrown, regular factories or jobbers .....	53	725	0.4	1.1	1.5
Silverware and plated ware	150	793	0.6	0.6	1.2
Soap and glycerin.....	264	3,246	0.9	0.2	1.1
Soybean oil, cake and meal	47	1,106	1.1	1.4	2.5
Special dairy products	51	283	0.2	0.3	0.5
Special industry machinery, not elsewhere classified	207	862	0.7	0.8	1.5
Sporting and athletic goods, not elsewhere classified	350	814	0.5	0.8	1.3
Springs, steel (except wire) .. . . .	53	761	2.1	1.2	3.3
Stamped and pressed metal products (except automobile stampings) .....	655	2,982	0.7	1.0	1.7
Steam engines, turbines, and water wheels	18	415	1.2	0.5	1.7
Steam fittings, regardless of material. ..	181	2,095	1.0	0.9	1.9
Steam and hot-water apparatus .....	68	1,441	2.1	1.1	3.2
Steam and other packing; pipe and boiler covering.	134	968	1.9	0.7	2.6
Steel barrels, kegs, and drums .. . . .	64	608	0.4	0.8	1.2
Steel castings .. . . .	164	8,614	2.7	3.6	6.3
Steel works and rolling mills .. . . .	253	161,794	4.6	1.3	5.9
Stokers, mechanical, domestic, and industrial ..	61	364	0.7	0.8	1.5
Stoves, ranges, water heaters and hot-air furnaces (except electric) .....	449	4,072	1.1	0.7	1.8
Surgical supplies and equipment; orthopedic appliances	360	664	0.3	0.5	0.8
Tableware, pressed or blown glass, and glassware	115	7,609	6.5	1.4	7.9
Tanning materials, natural dyestuffs, mordants, assistants.....	158	952	1.8	0.4	2.2
Terra cotta .. . . .	12	304	7.8	1.8	9.6
Textile machinery .. . . .	300	1,520	0.8	0.8	1.6
Tin cans and other tinware not elsewhere classified	248	2,832	0.4	0.4	0.8
Tires and inner tubes .. . . .	53	8,791	0.7	0.8	1.5
Tools (except edge tools, machine tools, files, and saws)	387	1,875	1.3	1.2	2.5
Tractors .. . . .	30	3,568	0.9	0.5	1.4
Upholstered household furniture .. . . .	853	1,090	0.3	0.5	0.8
Vegetable and animal oils, not elsewhere classified ..	54	525	1.0	0.7	1.7
Vitreous-china plumbing fixtures .. . . .	25	968	3.7	0.7	4.4
Vitreous-enameled products, including kitchen, household utensils .....	55	1,757	2.4	1.6	4.0
Wallboard (except gypsum), insulation (except mineral wool).....	124	2,456	3.2	3.7	6.9
Wallpaper.....	46	401	1.0	0.6	1.6
Whitewear .. . . .	31	1,207	3.4	1.0	4.4
Window shades.....	273	277	0.7	0.4	1.1
Wines .. . . .	301	513	0.7	0.9	1.6
Wire drawn from purchased rods	95	4,829	1.3	1.4	2.7
Wirework not elsewhere classified	669	2,398	0.6	0.9	1.5

**Table 15-21. Relation between Fuel Cost and Value of Manufactured Products.<sup>1</sup>**  
(Continued)

Industry	No. of plants	Total fuel and electricity cost <sup>a</sup>	Per cent of value of products		
			Fuel	Elec- tricity	Total
Wiring devices and supplies	146	1,287	0.7	0.7	1.4
Wood naval stores . . . . .	25	360	1.7	0.8	2.5
Wood preserving . . . . .	218	2,092	1.6	0.4	2.0
Wood products not elsewhere classified . . . . .	886	1,178	0.5	1.2	1.7
Woolen and worsted manufactures, contract factories	76	748	3.2	2.5	5.7
Woolen and worsted manufactures, regular factories or jobbers . . . . .	583	12,465	1.2	0.6	1.8
Wrought pipes, welded and heavy riveted . . . . .	49	1,770	1.3	1.0	2.3
Totals and averages (254 categories) . . . . .	146,731	1,260,626	1.72	1.01	2.73



## **SECTION 5**

### **PREPARATION OF COAL FOR UTILIZATION**



## CHAPTER 16

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### TREATING AND DRYING COAL

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# CHEMICAL TREATMENT OF COAL AND COKE<sup>1</sup>

## FUEL SAVERS

The idea that the burning of fuels can be improved by mixing or pretreating them with chemicals dates back to the early years of the last century. Various patent claims include the specific beneficitions of elimination or reduction of soot, smoke, and clinker; reduction of the ashes, presumably meaning the total weight of the refuse from the ashpit; elimination of sulphur fumes; increase in the rate of burning; increase in the time a given charge of fuel would last; and, in most patents, a saving of fuel. Earlier patents specified additions up to 80 lb or more per ton of fuel, but since 1860 the quantity has rarely been more than 4 lb.

**General Conclusions.** After an exhaustive investigation, the U.S. Bureau of Mines<sup>1</sup> reported that the tests of Eastern coals treated with over 25 such proprietary products showed that the treatments made no difference in the results within the range of duplication possible in tests of commercial boilers operated under conditions simulating normal operation. The tests definitely disproved the claims of the vendors for large saving of fuel, elimination of smoke and soot deposits, reduction of clinkering, or any other change measurable in such tests. Similar tests using Rhode Island anthracite also gave negative results.

The activating ability<sup>2</sup> of high-temperature coke, as measured by the average rate of burning (overfeed), was increased, particularly at low rates of combustion by some of the chemicals tried. Sodium carbonate and molybdenum oxide were the more active. The improvement in activity decreased very rapidly with increase in the rate of burning. With a treatment of 40 lb of sodium carbonate per ton of coke, the average rates of burning per square foot per hour were as follows:

Rate with no treatment, lb	1 2	3 0	3 4	9 7
Increase with treatment, per cent	22	10	8	4

In underfeed tests only negligible increases in activating effect were observed with heavy treatments of sodium carbonate.

No treatment was found positively to decrease the quantity of tar and soot in the gases at the stack.

Neither light nor heavy treatment decreased either the maximum density of the smoke or the total quantity of smoke. The average tendency was for the smoke to be increased slightly by treatments.

No chemical or treatment improved the nature of the clinkering. With the heavy treatments of 40 lb per ton, the quantity of clinker was increased and the slag was fused more thoroughly if the addition of the chemical lowered the ash-fusion temperature.

**Reduction of Caking.** The one definite effect of treatments that could be beneficial in the burning of coals is that they may reduce the caking in the bed for those coals which are not themselves strongly caking. This power to reduce caking amounts to a small but definite effect, which, when subtracted from the normal ability of the coal to cake, will make a large difference with a weakly caking coal but no measurable change with a strongly caking coal.

The ability of treatments to reduce caking had the following limitations: (1) it

<sup>1</sup> NICHOLLS, P., W. E. RICE, B. A. LANDRY, and W. T. REID, *Burning of Coal and Coke Treated with Small Quantities of Chemicals*, *U.S. Bur. Mines Bull.* 404, 1937.

<sup>2</sup> Increase in reactivity means that in a fuel bed more fuel will be gasified for the same amount of air passing through it, other conditions being equal.

decreased with decrease in thickness of the layer of coal fired and, even with the weakest caking coal used (Illinois No. 5), it was negligible with a thin firing; (2) it decreased with increase in air rate but not to the extent that it did with decrease in thickness fired.

Sodium carbonate was, on the average, the most effective of the chemicals in reducing caking. Boric acid, molybdenum oxide, and calcium chloride ranked next, were of about equal effectiveness, and in some individual tests did as well as the sodium carbonate. These ratings are based on the results with 20 to 40 lb of chemicals.

The effectiveness of the chemicals in reducing the caking power lay between being directly proportional to the amount used and to its square root. The effectiveness of 4 lb per ton was appreciable only with Illinois No. 6 coal and became increasingly negligible as the caking power of the coal increased.

A treatment with water alone also reduced caking. Water was the more effective with coals actually able to absorb water. With certain coals 8 per cent water was as effective as 2 per cent chemicals. As with chemicals, water was less effective as the caking power of the coal increased.

## DUSTPROOFING COAL BY CHEMICAL TREATMENT<sup>1</sup>

### Calcium Chloride

Among conclusions reached by Battelle Memorial Institute as to the use of calcium chloride as a dustproofing agent are:

1. Based on tests 1 week after treatment, calcium chloride satisfactorily reduces the dustiness of domestic stoker coals from seams having inherent or bed moisture contents of 8 per cent or less.

2. Coals of high inherent moisture content, of the order of 18 per cent, are not effectively treated with calcium chloride because of the rapid absorption of the treating material into the coal.

3. The dustiness of coals treated with calcium chloride increases with time of storage because of absorption of the treated material into the pores of the coal; but even after 3 months of indoor storage, the dustiness of coals having inherent moisture contents of 8 per cent or less is much less than for the untreated coals.

4. A high relative humidity should be maintained in the coalbin to decrease the dustiness of coal treated with a hygroscopic material such as calcium chloride. To do this the bin should be sealed from the basement to prevent air circulation and to keep the bin cool. Occasional sprinkling of the surface of the coal with water will also be helpful.

5. The rates of application required for effective treatment differ for various coals but are in the order of 7 to 10 lb calcium chloride per ton of coal for coals having inherent moisture contents of 8 per cent or less.

The Battelle experiments did not show a conclusive superiority of either the dry or the solution method of application of calcium chloride. If dry-flake calcium chloride is applied to dry coal, the addition of water at the time of treatment is advised to obtain rapid uniform distribution of the calcium chloride over the coal.

**Disadvantages of Calcium Chloride Treatment.** Scollon<sup>2</sup> has listed five disadvantages of calcium chloride treatment that have been claimed but not all definitely proved:

1. All chemical treatments using hygroscopic salts are of a corrosive nature.
2. Rain washes off the treatment.

<sup>1</sup> From SHERMAN, RALPH A., and GEORGE W. LAND, *The Dustless Treatment of Coals with Calcium Chloride and Other Materials*, Battelle Memorial Institute progress report.

<sup>2</sup> SCOLLON, R., *Problems Relating to the Dustproofing of Coal*, *Proc. 4th Ann. Coal Conf., West Va. Univ.*, 1941, pp. 91-95. For further data on coal treatments, see "Coal Preparation," Chap. 21, *Treatment of Coal Surfaces*, pp. 653-685, Seeley W. Mudd Memorial Volume, AIME, 1943.



3. Men object to working around calcium chloride mist.
4. Treating solution must be dissolved or diluted at the place of treatment.
5. Porous coals absorb calcium chloride and become as dusty as ever.

*Clarion Extract.* Battelle also tested a paper-mill liquor, Clarion extract. It was found not to be effective by itself in reducing the dustiness of coal, but the application at the rate of 3 gal per ton of coal of a solution of 2 parts of the extract with 1 part of water plus  $1\frac{1}{2}$  lb calcium chloride per gal solution was very effective in reducing the dustiness of one coal of 3.2 per cent inherent moisture (Elkhorn).

**Table 16-1. Amounts of Calcium Chloride Solution of Specific Gravity 1.22 Required for Various Ranks and Sizes of Coal<sup>1</sup>**

Rank	Size and use	Calcium chloride/ ton of fuel	
		Gal	Lb <sup>a</sup>
Anthracite .....	Buckwheat for stokers	$\frac{3}{4}$	$2\frac{1}{4}$
Anthracite ..	Prepared, domestic size	1	3
Bituminous: ..	Prepared, domestic size	$2\frac{1}{4}$	$6\frac{3}{4}$
High-volatile ..	Lump, egg	1	3
High-volatile ..	Stoker; nut, pea, slack	$2\frac{3}{4}$	$8\frac{1}{2}$
Low-volatile ...	Low for domestic use	$2\frac{1}{4}$	$6\frac{3}{4}$
Semibituminous ..	All	3	9
Coke ..	Household grades and sizes	2	6

<sup>1</sup> Recommendations of Michigan Alkali Co.

<sup>a</sup> As used in dry-flake form instead of solution.

### REMOVAL OF SOOT BY THE USE OF SALTS OR COMPOUNDS<sup>1</sup>

According to a popular belief of long standing, flues and furnaces can be cleaned of soot accumulations by throwing common salt on the fire. As an alternative to common salt, zinc wastes, old dry batteries, and even tin cans have been used. There are also a number of patented or proprietary compounds or mixtures sold under the general names of soot removers or chimney cleaners. The claims in the advertising matter on such preparations sometimes include those of preventing the formation of smoke and the deposition of soot.

**Theory and Effectiveness.** The action of soot removers is to produce conditions so that the soot will ignite at a lower temperature and burn more easily. There is none of that magic action which is often implied in the sales material. The effectiveness of the burning varies with the composition of the remover but is also largely a matter of chance of the condition being favorable. They will usually produce at least some reduction of the soot in the furnace and flue pipe, but their action does not often extend to the chimney. They have no effect on the ash mixed with the soot. This ash not only does not burn and must be removed by hand as before, but it also prevents complete burning of the soot mixed with it.

The Bureau of Mines investigation showed that, insofar as a material thrown on the fire may remove soot, it is done by the process of the material burning or being volatilized and forming a vapor or smoke which settles on the surface of the soot; it was further shown that a deposit of many metallic salts, particularly chlorides, will lower the temperature at which soot will catch fire and, when once ignited, will make it burn more vigorously (see Table 16-2). For the soot to be able to burn, the gases in contact with the soot must have a high enough temperature to ignite it, and they must contain

<sup>1</sup> NICHOLLS, P., and C. W. STAPLES, Removal of Soot from Furnaces and Flues by the Use of Salts or Compounds, *U. S. Bur. Mines Bull.* 360, 1932.

some free oxygen. Only with this combination of conditions may there be a beneficial result from the use of soot removers.

Table 16-2. Ignition Characteristics of Soot as Treated with Various Salts<sup>1</sup>

Compound used	Max without ignition, deg F	Max with ignition, deg F	Ignition mean temp, deg F	Decrease from 1135°F in air	Remarks
None (pure soot)	1225	1047	1135		
Zinc 20 per cent, salt 80 per cent	879	862	871	264	Good deposit
Stannous chloride	868	850	859	276	Good deposit
Brass filings 20 per cent, salt 80 per cent	859	850	855	280	Poor deposit
Lead 20 per cent, salt 80 per cent	850	847	853	282	Dense fumes
Red lead 50 per cent, salt 50 per cent	829	799	814	321	
Lead carbonate 20 per cent, salt 80 per cent	799	795	797	328	Dense fumes
Copper 20 per cent, salt 80 per cent	739	709	724	411	Similar to salt
Copper sulphate 20 per cent, salt 80 per cent	754	739	747	388	Did not sublime well
Cupric carbonate 20 per cent, salt 80 per cent	709	673	691	444	Did not volatilize well
Common salt	976	962	969	166	Good fumes
Calcium chloride	921	901	911	224	Fumes not dense
Chloride of lime	918	889	904	231	Fumes not dense
Zinc chloride	915	885	900	235	Good fumes and deposit
Ferrie chloride	903	895	899	236	Fair fumes with chlorine

<sup>1</sup> Condensed from a more extensive table in *U.S. Bur. Mines Bull.* 360, p. 19, Table 5, 1932.

**Relative Effectiveness of Various Materials.** All the proprietary materials investigated contained one or more ingredients which had been found to be more or less effective in aiding the soot to ignite and burn; the other ingredients in some are useless but otherwise do no harm. Common salt in large percentages occurs in most of them, and some consist entirely of common salt mixed with some powder to color and disguise it.

A large number of metallic salts are more or less effective, the effectiveness of the deposits formed by using the more common chlorides being in the increasing order of common salt, chloride of lime, zinc chloride, tin chloride, lead chloride, and copper chloride. However, a householder is limited to such materials as can be purchased at retail stores at reasonable prices. Very few of the materials found to be most effective can be so purchased, but a few are suggested as follows:

**Common salt**, in the form of rock salt or ice-cream salt. While this is the most available and cheapest material, it is not the most effective; there should thus be a good bed of very hot coke when common salt is used. Two or three teacups are sufficient for the average domestic furnace.

**Chloride of lime**, which is sold as a disinfectant, bleaching powder, etc. It is more expensive than common salt, and it is questionable as to whether it will be found to be more effective.

**Mixture of dry red lead and common salt** in proportions of 1 lb red lead (purchased at paint and hardware stores) to 10 lb salt. One heaped teacup per application on average furnaces, two for large furnaces.

**Mixtures of dry white lead and common salt**, more difficult to buy but better than red lead because it vaporizes more readily. The carbonate of lead must be used and not the sulphate. The mixture should be 1 lb lead to 5 lb salt.

The two lead mixtures are the most effective that can be made from readily available materials and were found to be more effective than any proprietary compound

available at the time of the investigation. **Caution:** Lead salts are poisonous and should be used with extreme care. Do not touch with the hands or inhale the powder. Do not close the stack dampers to a point where the fumes will escape into the cellar.

**Old dry-cell batteries** contain the required ingredients. It has been established that, when they are thrown in a hot furnace, the soot usually burns. Because of their size, they are slow in burning, and quicker action will be obtained by chopping them up.

**General Instructions.** Start with plenty of fuel, burning well. Clear a portion of the surface to exposed red-hot coke. Close the ashpit damper and fire-door slots, and scatter the remover over the red-hot coke. Reduce the draft by closing the choke damper or opening the check damper, but not enough to cause smoke to discharge to the cellar. Let the remover "stew" in this way for 10 to 20 min. Then let the fire burn as fiercely as it will by damper manipulation. Remember that there must be oxygen in the gases at this phase, so open the fire-door slots or even the door (slightly). The success of the cleaning will then still be subject to considerable chance. However, there is one further step which can be taken, *viz.*, to throw wood (preferred) or paper on the fire. It is well known that soot can be burned out without using a remover, provided that enough paper is burned in the furnace.

The chances of success are greater in a warm-air furnace than in a steam or hot-water heater because of the hotter flue gases.

Chances of success with cookstoves are very questionable because of low combustion rates.

**Hazards Involved.** The burning of the soot seldom extends beyond the smoke pipe. However, this will sometimes get red hot, and occasionally soot will burn in the chimney. Thus compounds should not be recommended unless the chimney is known to be in good condition, if the roof is of a type likely to be set on fire by burning soot.

**Ineffective with Anthracite.** Anthracite produces fly ash but not soot. In fact, soot found in anthracite-burning furnaces may always be traced to the burning of garbage or paper, to the starting of fires with other fuels, or to the previous use of other fuels. No soot remover or chemical which can be employed will affect fly ash or unburned coal. In fact, even when bituminous coal has been burned, the soot remover will leave such materials to be scraped out manually. Thus, soot removers should not be tried unless the material is known to be soot.

## FREEZEPROOFING TREATMENT

1. **Oils and oily substances** which make the coal surfaces resistant to wetting and mechanically deter cementing of the coal particles by freezing. Oil treatment of stoker coal and nut slack grades requires 3 to 12 gal per ton sprayed on the coal. This will prevent freezing in moderately cold weather. Further, the oil will not corrode the cars, the coal-handling, and the storage equipment.

2. **Water-soluble salts** that reduce the freezing temperature of the water. Any given concentration of salts has a given depression of the freezing point. Hence the coal may be conditioned to meet any anticipated freezing weather. Table 16-3, compiled by Bituminous Coal Research, Inc., shows recommended quantities of rock salt or calcium chloride for freezeproofing coal shipments. Some of these same materials are also used to "dustproof" the coal, particularly domestic coal.

However, the treatment may be partly nullified by dilution with rain or snow, or the salt may be carried away by draining out with the initial water. Cheap salts most commonly used for freezeproofing treatment are commercial calcium chloride or rock salt. These salts will generally have a corrosive effect on the coal-handling and storage equipment. In some cases, these salts will tend to form agglomerations on

**Table 16-3. Recommended Quantities of Rock Salt or Calcium Chloride for Freeze-proofing Coal Shipments**

Temp, deg F	Surface moisture, per cent			Temp, deg F	Surface moisture, per cent		
	3	6	9		3	6	9
	Lb/ton of coal treated				Lb/ton of coal treated		
20	3 4	6 8	10 2	-10	8.2	16.4	24.6
10	5 0	10 6	15 0	-20	9 2	18 4	27.6
0	6.6	13 2	19 8				

stokers. There are several suitable proprietary treatment reagents in which the base salt is modified to improve its effectiveness for special conditions and to mitigate the corrosive effect on equipment (see Table 16-4).

**Table 16-4. Preventive Treatment Materials, Soluble Salts, Oils, and Compounds**

Material	Source of Supply
Compound M Coaladd Oiladd	Johnson-March Corp.
Calcium chloride.	The Dow Chemical Co. Wyandotte Chemicals Corp. Solvay Sales Corp. Pittsburgh Plate Glass Corp.
Sealite.	Midland Sealite Corp.
Coal-spray oils	Standard Oil Co. of N.J. Texas Co.
Oil-spray equipment	Viking Mfg. Co. J. C. Corrigan Co.

**Methods of Applying Salt Treatments.** Where it is desired to "dustproof only," the salt is sprayed on the coal in the form of an aqueous solution. However, where it is desired to freezeproof the coal, it is considered better to add the dry salt to the coal to avoid adding more water. For even application of dry salt, this can be achieved mechanically. For most effective application, the salt may be concentrated at the sides and the bottom of the car, where it is first subject to cold penetration. This type of distribution is expensive, since it must be a hand operation.

Some shippers treat the coal very heavily over the car hoppers, to ensure that the unloading will at least start. The remainder of the coal may then be more readily broken out by means of bars. Even if freezing is not entirely prevented, freezeproofing is helpful in unloading and handling.

For severe cold conditions, because the freezeproofing is costly, it is probably more economical to freezeproof partly and apply heat or mechanical aids, or both, at the unloading point. Generally a combination of some heating system and a mechanical aid is utilized. For detailed descriptions of some of the mechanical agitators, refer to Chap. 18.

**Salt Detrimental to Stokers.** Common salt is likely to cause very serious combustion difficulty on certain underfeed stokers, because of its precipitation and collection on the cooler parts of the retort to block air holes and even coal passage.

**Preventing Frozen Coal.**<sup>1</sup> Frozen coal shipments are a result of the freezing of free surface water collected in the interparticle spaces. This water is usually a residue of the coal-cleaning process to reduce ash-forming impurities.

<sup>1</sup> KRAMER, A. W., More on Handling Frozen Coal, *Power Generation*, vol. 52, No. 9, pp. 74, 75, September, 1948.

**Preventive Treatment.** Well-screened, washed, and prepared sizes drained on screens generally will not freeze, since the water tends to run freely from coal free of fines.

Screenings and slacks will retain more surface water. To free them of serious freezing in moderate weather, they may be centrifugally dewatered, but thermal drying is more effective. Even with thermal drying, shipments of open-top cars are vulnerable to the weather. Slack  $\frac{3}{8}$  by 0 is generally considered to be safe from freezing if surface moisture is less than 5 per cent before shipment. However, conditions of degree of exposure to decreased temperature, moisture, and distribution of moisture through the car vary so widely that it is unsafe to set up a definite specification that will assure freedom from freezing.

## COAL DEWATERING AND DRYING

### COAL DEWATERING<sup>1</sup>

Moisture, which can be removed by heating the coal up to 100°C (212°F), may be retained in various forms:

1. As a film, on the surface of each coal particle, and in the interstices between particles, retained by capillary forces.

2. Moisture "occluded" inside the coal particles. This may be either free moisture (as in a sponge) or hygroscopic moisture which varies with atmospheric conditions (also called "regain").

The latter forms of moisture are particularly common in young coals (subbituminous and lignites), bloom coals (seam outcrops), fusain, and carbonized products.

The remainder of this section considers only the removal of free moisture, exclusive of hygroscopic moisture.

**Table 16-5. Comparison of Dewatering and Drying Equipment**

Type	Material size best adapted	Advantages	Disadvantages
Drain, shaking screens, etc. Filters	+1½ to 3½ in. Fine-coal sludge	Process simple and inexpensive Discharge water fairly clear. Less space than settling pond	Choking of perforations, mesh. Slime discharge in effluent water Must be flocculated for efficient filtration. Product usually requires thermal drying for final moisture elimination
Centrifugal ...	—¾ to 48 mesh	Large capacity with small space requirement. Dewater more rapidly with drier product than any other method other than heating. Low power consumption	Preliminary dewatering over shaking screen to help performance and efficiency. Slime discharge in effluent water. Degradation of product. Product having high per cent close to 48 mesh causes wear of screens
Thermal drier..	Sludge, to 1½ in. depending on design	No slime-bearing effluent water. Possible to produce product with zero per cent moisture	Highest cost per ton of coal handled. Equipment most complicated. Degradation in larger product sizes in rotary types

The term **drying** is usually reserved for the removal of water by evaporation, while the initial phase of the mechanical removal of free moisture is a distinct operation, covered by the term **dewatering**.

In all cases, the free water carried over the surfaces of the coal particles or in their interstices or in their pores is retained by capillary forces. Dewatering is accomplished by breaking or counteracting these capillary forces. Removal of as much

<sup>1</sup> VISSAC, G. A., A Technical Study of Coal Drying, *Trans. ASME*, February, 1949, pp. 56-60.

water as possible by dewatering methods is usually advisable, as the cost of these operations is generally much less than by evaporation.

The most common methods of mechanical dewatering are:

1. **Pressure piling**, which reduces the interstitial spaces, accomplished in dewatering bins or over dewatering screens.

2. **Dynamic methods**, such as used in centrifuges or over vibrating screens.

3. A third method, **preferential wetting**, in which surface water can be displaced by hydrocarbons, offers possibilities but is not yet in extensive practical use.

As the capillary forces retaining water on the coal surfaces decrease considerably with increased temperatures, a popular type of drier includes a dewatering section. As the coal enters the drier and is gradually brought up to higher temperatures, its dewatering ability is increased, and advantage can be taken of this condition to result in increased drying efficiencies and reductions in drying costs.

**Drainage.** The choice of dewatering methods depends on the size of coal, the amount of moisture reduction desired, and the size of the washing plant. For dewatering plus approximately  $\frac{1}{2}$ -in. coal where the preparation process is relatively simple and inexpensive, there are a number of methods: (1) drainage hoppers and bin; (2) conveyors and chutes fitted with slots; (3) round-wire, wedge-wire, and slotted stationary screens; (4) shaking screens; and (5) perforated bucket elevators.

For drainage dewatering of sizes under approximately  $\frac{1}{2}$  in. the same type of equipment used on coarse sizes is employed. To secure complete drying, centrifuges, suction filters, dewatering elevators, and screens must be used in connection with sludge tanks and thermal drying.

Table 16-6. Washed Coal Dewatered on Shaking Screens

No.	Size of product dewatered		Per cent surface moisture
	Range	Mean	
1	2 × 4 in.	3 00	1 1
2	2 × 3 in.	2 50	1 5
3	1½ × 2 in.	1 56	1 8
4	¾ × 2 in.	1 18	3 6
5	¾ × 1¼ in.	0 81	4 2
6	28-mesh × ¾ in.	0 23	11 5
7	48-mesh × ¾ in.	0 156	16 6
8	60- × 14-mesh	0 027	23 3

NOTE: Where the final moisture desired on fine-coal slack is below approximately 10 to 15 per cent and where transit is short, it is necessary to install dewatering equipment of different types, such as centrifuges or heat driers.

**Filtration.** Filters are used in the dewatering of froth-flotation concentrates and fine-coal slurries from thickeners; they may also be used to remove fine refuse from wash water to prevent stream pollution. Filtered coal usually requires further dewatering by heat drying.

The rate of filtration is greatly affected by the size and spacing of the pores in the filter cloth. Proper pore size is desired to permit easy passage of the water and to allow bridging of the solids over the pore for the building of the filter-cake structure. Fast filtration occurs when the mean diameter of the particle size is greater than the mean pore spacing.

Filtration is usually, and more effectively, carried out with flocculated pulps. The Pittsburgh Coal Co. uses a starch coagulant to assist clarification in its thickeners and adds additional starch to the filter feed. Without flocculation, the slimes are first

sucked to the filter medium, which becomes partly blinded. With a flocculated pulp, each floc contains coarse and slime particles and the floc is drawn to the filter medium, depositing coarse particles quickly. The coarse particles form a screen on the filter cloth, which protects the filter medium from being blinded by the fines. The filtration rate of a dispersed slime may be 50 to 200 times slower than when flocculated. Flocculation generally is carried out in both thickening and filtration, since these operate sequentially. Careful control of flocculation is essential for satisfactory filter operation.

Continuous-suction filters are the only kind that are used commercially for filtering coal slurries in the United States. The intensity of the force that can be applied between the sides of the filtering medium of suction-type filters cannot be greater than

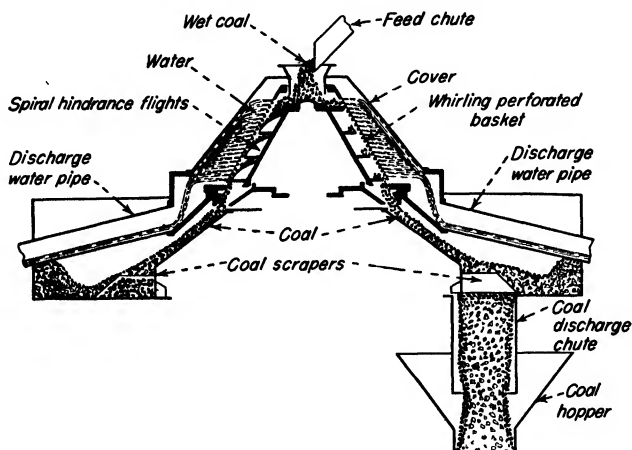


FIG. 16-1. Centrifugal and mechanical industrial drier. Diagrammatic representation of centrifugal drier—none of the driving gear shown. Water is squeezed through the perforations of the basket screen which is revolving at a slightly higher speed than the spiral hindrance flights. Coal scrapers revolving at relatively low speed carry the coal around to the coal discharge chute. This type is also available with a gravity discharge instead of the coal scrapers.

1 atm (30 in. Hg). To maintain a high vacuum, a bed of  $\frac{1}{2}$  to  $\frac{3}{4}$  in. must be carried to prevent undue passage of air through the bed.

**Centrifugal Drying.** Centrifugal drying is a rapid mechanical method for drying slack sizes of coal, usually  $-\frac{3}{8}$  in. in size. In this method, the washed coal is subjected to a spinning action in a perforated basket, the water being forced out of the basket through the perforations. One of their great advantages is the handling of fine coal with a considerable amount of free moisture present. This type of drier will take fine-coal feed with as much as 80 per cent free moisture and deliver a product with a relatively low moisture content of 5.5 per cent. Other advantages include the utilization of a small amount of floor space and the fact that the power consumption is not excessive. While machines of the intermittent type are generally used in the drying of most industrial products, the drying of coal requires the use of a continuous machine in order to secure high capacity, a product of uniform moisture content, and consistent physical and chemical properties.

Since centrifugal driers tend to cause degradation of the product because of high rotational speed, it is advisable to treat sizes that have already broken down to natural cleavage, such as  $\frac{3}{16}$  to 48 mesh, or at most,  $\frac{3}{8}$  to 48 mesh. If a large amount of 48 mesh is present, maintenance will be high, since the passage of fines through the

basket with the effluent rapidly wears the cloth of the basket. Preliminary dewatering over shaking screens helps performance and reduces maintenance.

The moisture content to which  $-\frac{3}{8}$ -in. coal can be reduced is dependent upon such factors as amount of feed, size characteristics of the feed, percentage moisture of the feed, amount of screen surface, size of screen perforations, and thickness of beds on screens. Tests have shown that frequently a reduction of both sulphur and ash occurs in the dried product as compared with the feed. The treatment of the effluent obtained in centrifugal drying still remains a problem.

The **C-M-I drier** (Fig. 16-1) is a continuous type, vertical axis, consisting of two rotating units, an outside conical screen frame and an inside solid cone carrying spiral hindrance flights. Both units rotate in the same direction, but the screen unit moves

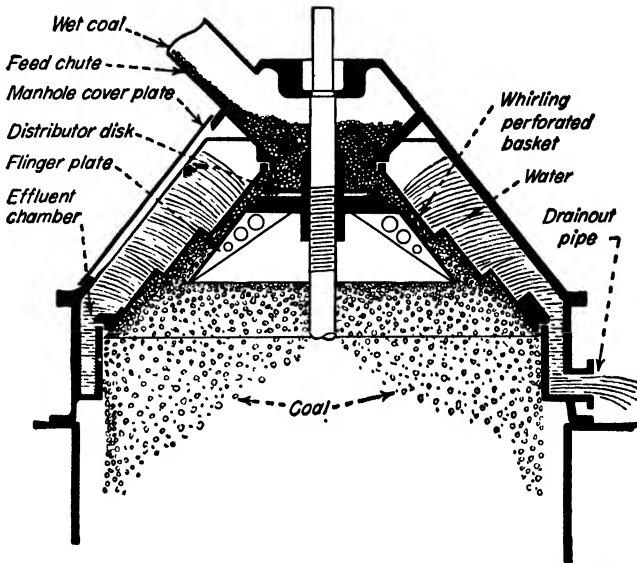


FIG. 16-2. Carpenter drier. Diagrammatic presentation of a centrifugal drier—none of the driving gear shown. Centrifugal action forces the water out of the coal through the perforations in the three-step basket. (*McNally Pittsburg Mfg. Co.*)

slightly faster than the cone carrying the spiral flights. The feed enters the machine at the top and falls down on the cone where the centrifugal force throws it against the screen. It slides down the screen until it meets the upper end of the flights and gradually finds its way to the bottom of the screen cone.

The **Carpenter drier** (Fig. 16-2) is the vertical type. The machine consists of a rotating conical unit with perforated screen sections which are cut and rolled to form the surface of the cone. The wet feed material is delivered to a small conical hopper inside the drier casing and is distributed by a distributing disk to the top of the screen sections in an even layer. The thickness of the layer can be adjusted by raising or lowering the distributing disk. The material is thrown against the top screen and starts to progress downward, releasing moisture as it advances over the screen surface (see Table 16-7).

The **Bird centrifugal filter** is primarily used for dewatering slurries. It is a horizontal type, and, unlike the Carpenter and the C-M-I, it requires no baskets or screens. This machine has two rotating units, a bowl and a screw conveyor. The bowl is in the shape of a truncated cone. The screw conveyor rotates inside the bowl at a



slightly lower speed in the same direction of rotation. The solids are moved forward by the conveyor as fast as deposited, being carried above the level of the effluent or filtrate for an interval before leaving the bowl. Adjustable effluent-discharge ports are located in the large end of the bowl so that the level of liquid is maintained at a desired height. The dried product and the filtrate are discharged continuously, at opposite ends of the bowl, and can be conveyed where desired.

Table 16-7. Moisture Reduction and Relation of  $-\frac{3}{8}$ -in. Coal<sup>1</sup>

Item	Moisture in feed, per cent	Moisture in discharge, per cent	Size ratio in feed <sup>a</sup>						
			No. 4	No. 10	No. 14	No. 48	No. 100	Minus No. 100	Minus No. 48
1. Dewatering elevator <sup>b</sup>	75 0	26 0	24 0	....	38 5	28.0	4 5	5 0	
2. Dewatering screen <sup>c</sup>	75 0	18.0	18.0	....	42 5	31.0	5 5	3 0	
3. Carpenter driers, AR-12	22 5 <sup>d</sup>	6.5	24.0	....	38.5	28 0	4.5	5 0	
4. Carpenter driers, AR-1A	23 3 <sup>d</sup>	5.2	20.0	....	44 5	30.0	3.5	2 0	
5. Carpenter driers, AR-1B	19 0	9.1	19.5	....	36.5	31 5	7.5	5 0	
6. Carpenter driers, AR-4 <sup>f</sup>	20 2	7.2	....	69.3	8 7	20.0	.		2 0

<sup>a</sup> Tyler standard-screen sieves, sizes in mesh.

<sup>b</sup> Elevator discharges onto distributing conveyor, which feeds AR-12 driers.

<sup>c</sup> Dewatering screen discharges onto distributing conveyor, which feeds AR-1 drier (item 4).

<sup>d</sup> After passing over 9 ft of  $\frac{1}{2}$ -mm wedge wire in distributing conveyor.

<sup>e</sup> Receives feed from dewatering elevator and storage bin

<sup>f</sup> The AR-4 type, operating on Pittsburgh seam other than Pittsburgh Coal Co. and handling  $-\frac{5}{8}$ -in. coal.

<sup>1</sup> CUDWORTH, JAMES R., and ELLIS S. HERTZOG, Dewatering and Drying Coal, *U.S. Bur. Mines Inform. Circ.* 7009, 1938.

Table 16-8. Performance of Carpenter Drier<sup>1</sup>

Feed, tons/hr	45	35	35	40
Moisture in feed, per cent	18	27	26	17
Surface moisture in product per cent	6	7 5	7 3	4 0
Size of feed	$\frac{3}{8}$ in. $\times$ $\frac{1}{2}$ mm	4 m $\times$ 0	4 m $\times$ 0	$\frac{3}{8}$ -in $\times$ 0

<sup>1</sup> The McNally Pittsburg Mfg. Corp.

There are two general uses for Bird filters in the industry. The first of these is the dewatering of clean coal, say  $-\frac{3}{8}$  in. or finer, as discharged from the cleaning equipment, which might be tables, launders, heavy mediums, jigs, etc. The second use is in conjunction with water clarification, these machines being employed in those plants which must have a closed water system.

When handling  $-\frac{3}{8}$  in., the industry usually requires the largest filter which is built, the 54- by 70-in. size. This unit has a maximum capacity of about 50 tons dried coal per hr. The feed will contain anything from 25 to 40 per cent solids; the cake discharged from the filter will contain from, say, 5 to 10 per cent, the filtrate approximately 5 per cent solids. The moisture retained in the cake is dependent entirely on the quantity of fines, *i.e.*,  $-200$ -mesh coal, which is present in the feed. The greater the quantity of fines, the higher the moisture content in the cake. A typical example obtained from the installation at the Marianna plant of the Bethlehem collieries indicates a feed containing about 17 to 18 per cent  $-200$ -mesh fines. The cake discharged from the Bird filter contains about 8.5 per cent surface moisture, the filtrate about 7.5 per cent solids. This plant is operating with a closed water circuit,

and the solids in the filtrate build up to the figure shown and hold there. Power required is about 100 to 110 hp, or roughly 2 hp per ton.

The second use for Bird filters, *i.e.*, where the clarifying units are used, is usually employed in plants which either have a high clay content in the coal coming from the mine or employ a cleaning system such as a Chance cone, which requires a silt or degraded sand drawoff. In these plants a portion of the water, quantity determined by the amount of solids which must be removed to keep the water system in balance, is handled in 40- by 60-in. Bird clarifying units. The usual feed would contain, say, 15 per cent solids, the solids being all approximately -48 mesh in size. The cake from the Bird filter would contain about 25 per cent moisture and would usually be discarded with the refuse. The water in turn, which would contain from 1 to 3 per cent solids, is returned to the process for reuse. This size unit is usually driven with a 75-hp motor, and power demand is something on the order of 50 to 55 hp.

### THERMAL DRYING

**Heat Drying.** In the final phase, after dewatering, the remaining moisture must be evaporated. Coal and water must be brought up to the chosen temperature of evaporation, and heat must be supplied to fill the requirements of the latent heat of evaporation of the water to be removed.

Accordingly, drying becomes largely a problem of heat transfer, and drying methods can be classified accordingly, *viz.*:

1. Radiant transfer
2. Transfer by surface contact and conduction
3. Transfer by hot-gas contact

The first method is not applicable to coal drying; the second method is used in the old-type rotary driers; and the third method is the most commonly used in modern coal driers. In all but the smallest capacity driers, a continuous method of drying is to be preferred over batch methods.

The mechanism of **complete** drying is very complex, involving the several phases of:

1. The constant-rate period
2. The uniform falling-rate period
3. The varying falling-rate period

However, as coal rarely needs to be completely dried (under  $1\frac{1}{2}$  per cent), it is usually sufficient to consider **constant-rate drying** only, as has been done in the remainder of this section.

**Drying Characteristics of Coal.** Before attempting the design of a drying plant, it is essential to determine the drying characteristics of the coal to be treated, in other words, to establish the relative drying difficulties.

One method of such analysis consists in plotting the drying curves of the coals under consideration. Drainage factors are first established by allowing coal, fully saturated with water, to drain for a fixed period of time. The final moisture contents are based upon practical experience, coal characteristics, and actual requirements, and the hours required to reach this per cent moisture are considered the drainage factor of the coal at hand.

**Example.** If a given coal requires 12 hr to drain down to 10 per cent, the predetermined desired moisture, its drainage factor will be considered to be 12.

Drying factors are established in the same manner; coals are allowed to dry in a heated laboratory under certain constant conditions of evaporation. The hours required to dry from the final point of drainage to the required point of drying are considered to be the drying factor of the coal at hand.

This drying factor is controlled by a combination of the coal and size characteristics as well as by the particular requirements of the individual drying problem.

**Calculation of Drier Efficiency.** The efficiency of a heat drier is equal to the quotient of the heat actually used for evaporation, by the total heat supplied.

**Example** (Refer to Table 16-9, operation 1, hot gases at 400°F):

$$\frac{\text{Heat used for evaporation}}{\text{Total heat required by drier}} = \frac{102,400 \text{ Btu}}{169,000 \text{ Btu}} = 60.6\%$$

Similarly, in operation 2, from the same table, with the hot gases at 660°F, the efficiency may be shown to be 50 per cent. This thus provides a further illustration of the advantage of operating at low temperatures.

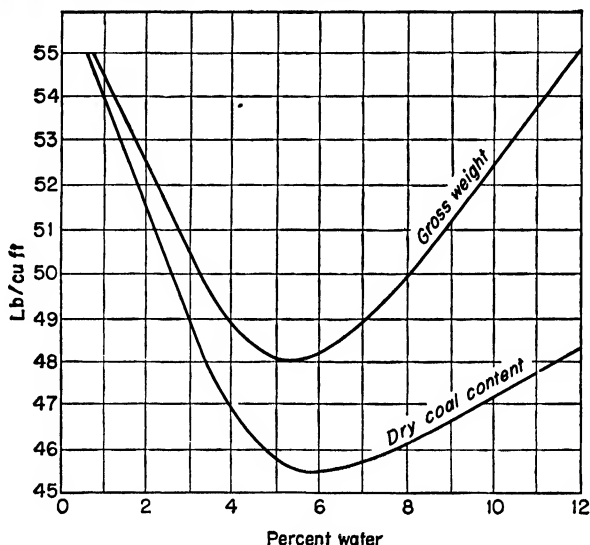


FIG. 16-3. Effect of moisture content on coal weight per cubic foot. (Price, J. D., and Bertholf, *Coal Washing in Colorado and New Mexico*, Mining Transactions AIME, April, 1949, p. 103.)

However, in arriving at the figure of 169,000 Btu in the example above, it had been previously assumed that only 75 per cent of the heat in the coal would actually be available for drying. Therefore, the total efficiency, or over-all efficiency, of the drying plant will be  $0.75 \times 0.606$ , or 45 per cent, for operation 1 and  $0.75 \times 0.50$ , or 37.5 per cent, for operation 2.

Cooling and regeneration will increase the above efficiencies materially.

Table 16-9. Typical Operating Data with Driers at Two Hot-gas Temperatures<sup>1</sup>

	Operation 1	Operation 2
Temperature of evaporation, deg F	120	140
Volume of hot gases, cfm	34,000	18,800
Temperature of hot gases, deg F	400	660
Btu required for:		
Evaporation (100 lb), Btu	102,000	101,800
Heating water and coal, Btu	36,000	48,000
Radiation loss, Btu	30,600	54,000
Total Btu/min	169,000	203,000
Total Btu/hr	10,140,000	12,198,000
Hp required for drier fan	50	27
Kwhr	38.5	20 25

<sup>1</sup> VISSAC, G. A., *Trans. AIME*.

For a true comparison of the efficiencies of various drying plants, other factors must be taken into consideration.

For example, it has been estimated that the exhaust gases from the drier will be at 75 per cent saturation. This is an actual minimum, obtained by experience, which applies to most driers. However, in actual practice this figure may have to be checked; a lower saturation will indicate lack of sufficient contact between coal and gases, because of faulty design or faulty operation.

**Drying at Low Temperatures Usually Desirable.** It is usually desirable to operate a coal drier at low temperatures, in order to obtain not only the maximum efficiency but also the best safety of operation. In this connection, it is important to know the kindling temperature of the material at hand. (Typical kindling temperatures are given in Table 11-15.)

Another frequent advantage of the operation of a drier at low temperatures is the possibility of using the exhaust gases available from existing boiler plants, or carbonization plants.

In order to operate at low temperatures and still handle large tonnages of coal, a coal drier must be able to handle proportionately large volumes of gases.

**Influence of Hot-gas Temperature.** Table 16-9 illustrates the effect and consequences of a change in the hot-gas temperatures. As is shown in the two arbitrary examples, increasing the hot-gas temperature from 400 to 660°F reduces the required volume from 34,000 down to 18,800 cfm, and the fan consumption from 38.5 kwhr of electricity to 20.25 kwhr, but the Btu required are increased by 2,000,000 Btu per hr.

Normally, with a drier adapted to take care of the increased volume, *i.e.*, the same water gauge, the operating balance is definitely in favor of the low temperature, *viz.*:

1. Operation 1, an increased power consumption of 18.25 kwhr, or 183 in a 10-hr day, or 91 cents per day

2. Operation 2, an increased coal consumption of 1 ton a day, worth considerably more

To give a wider picture of the influence of the hot gas temperatures, Table 16-10 has been prepared to show the corresponding volumes and temperatures with temperatures of evaporation (temperature of gases at the drier exhaust) of from 110 to 145°F.

**Table 16-10. Conditions Required for the Evaporation of 1 Lb of Moisture per Min<sup>1</sup>**

Temp of evaporation, deg F	110	115	120	125	130	135	140	145
Volume of hot gases required, cfm <sup>a</sup> . . .	495	405	340	289	251	220	188	167
Temp of hot gases in duct, deg F . . . . .	300	350	400	460	520	580	660	750

<sup>1</sup> VISSAC, A. G., *Trans. AIME*.

<sup>a</sup> As measured at 60°F and sea level.

### Factors Affecting Selection of a Type and Size of Drier<sup>1</sup>

In a recent very comprehensive study of drying characteristics and drier performance, Lyons and Richardson<sup>1</sup> listed the factors affecting drying rate or drier performance as follows: (1) the surface moisture percentage of the wet coal, (2) the surface moisture percentage of the dried coal, (3) the weight of the inlet gases, (4) the temperature of the inlet gases, (5) the temperature of the exhaust gases, and (6) the average particle size of the coal being dried. Surface moisture was considered to be critical, rather than total moisture, because the majority of the drying plants considered it

<sup>1</sup> LYONS, ORVILLE R., and A. C. RICHARDSON, The Thermal Drying of Fine Coal, *Coal Technol., AIME Tech. Pub.* 2399, vol 3, No. 3, 1948.

unnecessary to dry the coal to a moisture content lower than the seam or surface moisture content of the coal as mined.

**Relative Effectiveness of Various Drier Types.** Lyons and Richardson further found that an attempt to evaluate the several types of driers relatively was affected by so many variables, including all the above, that it was largely resolved into a question of local requirements and conditions, without much chance of a universal formula which would serve in broad application.

They concluded: "All of the types of driers included in the survey (rotary, screen, continuous pallet, flash, tray, and cascade) evidently can be operated with the same degree of effectiveness if each type of drier is used to dry the sizes of coal for which it is best suited, and the difficulty of the drying problem is given proper consideration." They listed the size applications as:

1. Screen-type driers are being used to dry the coarser sizes of coal treated. Inclusion of very fine coal in the feed results in the blinding of the screen and unsatisfactory operation. Three- to seven-tenths inches is considered a desirable particle size for screen-type driers.

2. Rotary-, tray-, cascade-, and continuous-pallet-type driers are being used to dry the intermediate sizes of coal. A good particle-size range for these driers is 0.125 to 0.375 in. The choice between the driers in this group is largely one of initial cost of the equipment and the operating economics possible with the particular equipment.

3. The flash drier is the only drier now being extensively used to dry very fine coal. Its best particle-size range lies below 0.075 in.

It should be noted that it is usually undesirable and often impossible to dry different sizes of coal in one type of drier.

**Effect of Load Changes.** Once a drier and furnace setup have been designed to comply with any given set of drier conditions, it is usually difficult to increase the load on the system while it is relatively easy to operate at a lighter load. This fact should be given careful consideration because it is quite common in coal-preparation practice for the load on existing equipment to be suddenly increased, sometimes by as much as 100 per cent or more. Slight increases can be taken care of by increasing furnace temperature and thereby the inlet temperature, or by speeding up the fan to increase the gas flow. Large increases in load on the drier are bound to produce an unsatisfactory product. A lightened load is easily taken in stride because, as the load drops off, the exhaust temperature will tend to rise, and either automatic or manually operated controls can be utilized to reduce the feed rate to the furnace and thus reduce the total heat input.

**Size of Drier to Use.** From the above it is evident that the selection of a proper and adequate size of drier is of utmost importance. The size of drier required can be determined from Fig. 16-4, for screen and rotary driers only. In the case of rotary driers, the area is in square feet of total cylinder surface active and must be converted to diameter and length by selecting a desired diameter between 7.5 and 12 ft and calculating the length. These figures represent average values and are subject to considerable variance. However, they do provide a rough guide to the sizing of rotary and screen driers.

**Thermal Efficiency of Driers.** In the past, the reference value used for comparing driers has been thermal efficiency. Lyons and Richardson, however, do not consider this to be a significant or useful value. They point out that thermal efficiency does not take into account numerous other important variables and that determination of efficiency is extremely difficult in field tests of many driers. They report that calculated thermal efficiencies are in error by as much as 25 per cent. Further complicating the problem, the amount of water removed by evaporation could only be approxi-

mated for the majority of screen-type driers, because considerable water was also removed by drainage.

The inherent design and method of operation of screen- and continuous-pallet-type driers is such that any advantage gained by removal of water by drainage is lost by increased radiation and unaccounted-for losses.

**Cost of Drying.** The factors cited by Lyons and Richardson as affecting the cost of drying were: (1) power requirements per unit of water removed, (2) heat input per unit of water removed, (3) man-hours of labor required per unit of water removed, (4) total amount of water removed or the capacity of the drier installation, and (5) maintenance requirements.

Kaiser,<sup>1</sup> in a discussion of the Lyons-Richardson paper, points out that their cost data are somewhat incomplete; nevertheless the following are given as being guides to cost trends and positions.

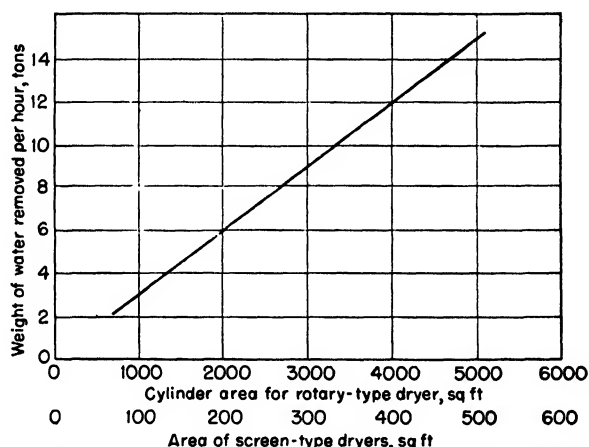


FIG. 16-4. Design data for rotary- and screen-type driers. (Lyons and Richardson, *AIIME, Tech. Pub. 2399, August, 1948.*)

In general, the operating cost of drying ranges from 8 to 18 cents per ton of dried coal produced, with the majority of the driers having costs of approximately 10 cents per ton.

On a basis of per ton of water removed, operating costs range from \$1.00 to \$3.00, with the majority of the driers having costs of approximately \$1.50 per ton of water removed.

**Capital charges,** based on the cost of the drier furnace, the drier, the duct work, exhaust fan, and exhaust stack, for a plant having one-shift operation for a 200-day year, assuming complete depreciation in 10 years, range from 4 to 12½ cents per ton of dried coal or 60 to 188 cents per ton of water removed.

**Maintenance,** a major item representing from one-third to one-half of the total operating cost of drying, could be reduced in many cases by (1) coating exhaust ducts, fan housings, and exhaust stacks to reduce corrosion; (2) the use of corrosion- and fly-ash-resistant fan impellers; (3) the use of stainless steel for exposed steel surfaces, such as screens; (4) adequate controls to prevent overheating of furnace and drier inlet ducts; and (5) a well-planned maintenance program.

<sup>1</sup> KAISER, E. R., Assistant Director Research, Bituminous Coal Research, Inc.

Table 16-11. Plant Operation and Results for Various Driers<sup>1</sup>

Drier type	Seam moisture, per cent	Surface moisture, per cent	Moisture in product (surface), per cent	Total kw-hr	Heat input /ton H <sub>2</sub> O removed, Btu	Temp, deg F		Avg particle size, m.	Out-put, tons/hr	Operating cost, dollars/ton H <sub>2</sub> O removed				
						Inlet gases	Outlet gases			Fuel	Power	Labor	Maintenance	Total
Rotary.....	6.5	5.0	-0.8	34.7	4,200,000	933	194	0.2883	66	0.54	1.72	0.36	0.13	2.75
	1.9	10.9	1.2	25.4	5,000,000	873	167	0.2886	40	0.56	0.20	0.29	0.38	1.43
	1.9	9.0	0.5	32.4	5,350,000	872	192	0.3210	37	0.65	0.24	0.36	0.44	1.69
	12.0	9.2	1.1	13.8	3,120,000	1014	150	0.2401	42					
	14.5	9.4	0.5	8.6	3,500,000	1227	166	0.1821	68					
Screen.....	2.25	12.5	5.0	15.5	2,740,000	1467	155	0.1353	147	0.28	0.14	0.31	0.23	0.96
	6.75	9.6	1.5	7.7	3,310,000	1275	145	0.2178	150	0.47	0.14	0.25	0.69	1.55
	13.0	3.2	0.6	26.0	4,510,000	958	155	0.3712	90	1.30	0.26	0.78	0.83	3.17
	16.4	4.0	-0.5	19.2	3,190,000	975	104	0.4774	145	0.45	0.36	0.62	0.45	1.88
	1.9	9.9	1.3	17.8	3,400,000	746	145	0.3540	68	0.46	0.17	0.26	0.26	1.16
	1.5	6.0	1.6	10.6	2,390,000	600	150	0.6472	117					
	9.5	7.0	2.0	19.7	2,700,000	900	97	0.5664	188					
	1.2	5.0	2.3	36.5	7,680,000	836	91	0.4414	42					
	1.1	10.4	3.8	11.2	1,790,000	786	93	0.3377	55					
	10.0	10.1	3.1	14.5	1,610,000	662	85	0.3046	141					
Flash.....	16.0	5.8	2.3	28.6	2,390,000	897	119	0.4914	192					
	14.0	3.0	1.3	43.6	9,540,000	566	61	0.5638	109					
	9.5	18.0	-2.7	17.0	4,980,000	1147	257	0.0642	9					
Cascade . . . . . Continuous pallet	1.9	9.4	2.9	7.4	5,000,000	756	161	0.0502	29					
	9.0	9.9	2.2	7.4	2,800,000	732	124	0.2713	30					
	9.0	12.1	8.7	15.4	2,540,000	805	97	0.2412	56	0.49	0.23	0.98	0.65	2.35
Revolving tray	9.0	8.3	3.2	15.6	3,670,000	736	103	0.2487	65	0.34	0.16	0.67	0.45	1.62
	10.0	6.8	1.0	11.9	3,930,000	732	106	0.2865	76	0.30	0.14	0.60	0.40	1.44
	16.0	10.3	1.1	5.4	2,740,000	917	134	0.2194	112					

<sup>1</sup> LYONS, ORVILLE R., and A. C. RICHARDSON, The Thermal Drying of Coal, *Coal Technol.*, August, 1948.

**Drier performance** could be improved in many instances by (1) eliminating heat losses due to air infiltration, (2) operating the drier at a steady rate, (3) making periodic check tests to determine drier effectiveness, (4) checking control instruments at regular intervals, and (5) having an intelligent drier operator.

**Table 16-12. Heat Balance of Three Types of Driers<sup>1</sup>**

Type.....	Screen	Continuous pallet	Rotary
Heat used in evaporating moisture in coal. . .	33 1	37 5	49.0
Sensible heat in coal processed.....	18.2	30.6	19.2
Heat lost in exhaust gases.....	13 8	13 4	16 4
Heat carried away by drainage water . . . .	1 5	2.0	0.0
Radiation and unaccounted (by difference).....	33 4	16.5	15.4
Total . . . .	100 0	100 0	100 0
Calculated furnace efficiency . . . . .	87 8	80 0	82.1

<sup>1</sup> KAISER, E. R., commenting on Lyons and Richardson paper, The Thermal Drying of Fine Coal, *Coal Technol.*, AIME, August, 1948.

### Example of Drier Calculations

The following concrete example serves to illustrate the proper method of calculating drier performance and requirements:

Assuming the feed of wet coal at the rate of 60 tons per hr with a free moisture content of 12 per cent, it being required to bring the free moisture content down to 2 per cent. We further assume that the drier will remove mechanically 5 per cent of moisture, leaving 5 per cent to be removed by heat drying.

**Volume of Gases Required.** A feed of 60 tons per hr equals 1 ton or 2,000 lb per min. Moisture to be removed is thus 5 per cent of 2,000, or 100 lb per min (dry basis).

Assuming evaporation at 120°F (temperature of gases at drier exhaust and 60°F as the outside temperature: 1 cu ft air per min carries, at 120°F and at full saturation, 0.005 lb water; at 60°F and full saturation, 0.001 lb water. The difference, or 0.004, represents the moisture that can be removed by 1 cu ft of air on a basis of evaporation alone, assuming 100 per cent evaporation efficiency.

Thus to remove 100 lb water, at an assumed evaporation efficiency of 75 per cent, would require (assuming sea level and 70°F)

$$100 \times \frac{75}{100} \times 0.004, \text{ or } 33,333 \text{ cfm}$$

**Temperature Required for Hot Gases.** If we call  $T$  this temperature,

$$33,333 \times 0.073 \times 0.25 \times (T - 120)$$

equals the number of Btu available when 33,333 cfm of gases, density 0.073, specific heat 0.25, cool off from  $T$  to 120°F (temperature of evaporation).

This amount of heat per minute must be sufficient to:

1. Evaporate 100 lb water at 120°F (latent heat 1024) or

$$100 \times 1024 = 102,400 \text{ Btu}$$

2. Heat the total coal and water from 60 to 120°F, viz.:

Coal:  $2,000 \times 0.25 \times (120 - 60)$  + water:  $100 \times 1 \times (120 - 60) = 36,000 \text{ Btu}$   
where 0.25 = the specific heat of coal.

3. Take care of radiation losses. On the basis of a drier with 2,000 sq ft of insulated surface and 2,000 sq ft of exposed surface, we have

$$2,000 \times 0.2(T - 60) + 2,000 \times 2.5(T - 60) = 90T - 5,400 \text{ Btu/min}$$



where 0.2 and 2.5 are the heat-transfer coefficients of the insulated and uninsulated surfaces.

The equation of heat balance thus becomes

$$33,333 \times 0.073 \times 0.25 \times (T - 120) = 102,400 + 36,000 + 90T - 5,400$$

from which  $T$  is found to equal 400°F.

**Total Heat Required.** As per the above, the heat required is the total of (1), (2), and (3), viz.:

$$(102,000 \text{ Btu/min}) + (36,000 \text{ Btu/min}) + (90T - 5,400 \text{ Btu})$$

which, with  $T$  as 400, equals 169,600 Btu per min, or roughly 10,000,000 Btu per hr.

**Furnace Required.** Total heat required, 170,000 Btu per min. With coal at 12,600 Btu per lb and 75 per cent combustion efficiency,

$$\frac{170,000}{0.75} \times 12,600 = 18 \text{ lb coal/min or } 1,080 \text{ lb/hr}$$

At 42 lb per sq ft, the required grate area would be 26 sq ft.

**Combustion space** at 50,000 Btu/cu ft/hr required equals 200 cu ft, thus requiring a 7.7-ft arch. (The latter assumes 300 per cent excess air, giving 15,000 cfm of hot gases to which 18,000 cfm of cooling air are added to give the required total of 33,000 cfm at the drier.)

**Rate of Evaporation.** The rate of evaporation of moisture is given by the formula

$$W = C \times V^{0.8} \times (e_w - e_a) \quad (16-1)$$

where  $W$  = lb water evaporated/sq ft/hr

$V$  = velocity of hot gases, fpm

$e_w$  = vapor pressure, in. Hg at water temperature

$e_a$  = vapor pressure, in. Hg in atmosphere

$C$  = a constant characteristic

The above formula illustrates the influence of the factors involved. A higher temperature of evaporation means a higher value for  $e_w$  but a lower volume of gases and a lower value of  $V$ .

**Time Required for Evaporation.** If  $Q$  is the heat energy conducted in time  $t$ , through a material of sectional area  $A$ , normal to the flow of heat and thickness  $D$  in the direction of the flow of heat, with a temperature difference  $T$  between its surfaces, then

$$Q = K \times \frac{ATt}{D} \quad (16-2)$$

or

$$t = \frac{QD}{KAT} \quad (16-3)$$

where  $K$  is a constant characteristic.

In other words, the time necessary to the required heat exchanges is reduced by the use of higher temperatures (factor  $T$ ), but this is partly compensated by the increased heat energy required (factor  $Q$ ).

However, the above formula clearly indicates the advantage of a large area (factor  $A$ ) in reducing the time required for the heat exchangers.

### Cooling and Regeneration

As the dry coal and the exhaust gases leave the drier at a temperature higher than when they were introduced, a certain amount of heat will be lost, pointing to the possibilities of increasing the efficiency of the drier by recuperating and regenerating the maximum possible amount of such heat. In addition to increasing the efficiency

of the drier, and, if the heat is so used, of effecting additional evaporation of the residual moisture, cooling reduces the danger of spontaneous combustion and decreases the sweating of the coal. Regeneration assists in the heating of the preparation plant, the thawing of frozen coal, and its mechanical dewatering (by reducing surface tensions).

Practical steps employed for extracting heat from the dried coal include:

1. Blowing cold air over the coal as it emerges from the drier
2. Spraying water into the drier exhaust and then using the heated water in a closed circuit to preheat the raw coal

Vissac shows that the air cooling of 2,000 lb coal per min from 120 to 70°F will extract 25,000 Btu per min. This amount of heat may be used for extra drying to the extent of 12.5 lb water or  $\frac{1}{2}$  of 1 per cent, with an expenditure of 12,500 cfm requiring 5 kw per hr and saving 120 lb coal per hr.

The formulas for these calculations are as follows:

**Heat Extracted from Air-cooled Coal.**

$$W \times sh \times (T_i - T_f) = \text{Btu extracted} \quad (16-4)$$

where  $W$  = weight of coal in unit time

$sh$  = specific heat of coal (approx 0.25)

$T_i$  = initial temperature of coal before cooling

$T_f$  = final temperature of coal after cooling

Btu will be in the same terms of time, as was  $W$  (in this case in minutes).

**Extra Weight of Moisture Evaporated.**

$$p = \frac{(\text{Btu}) - [V \times w_a \times s_a (T_f - T_i)]}{L} \quad (16-5)$$

where  $p$  = extra weight of moisture evaporated per min

Btu = heat available for evaporation, as in this case the heat extracted from the preceding formula

$V$  = volume of cold air, cfm

$w_a$  = weight of air, lb per cu ft at mean temperature

$s_a$  = specific heat of air (approx 0.25)

$T_f$  = final air temperature

$T_i$  = initial air temperature

$L$  = latent heat of vaporization of water

In cases where both  $p$  and  $V$  are unknowns, the above equation may be solved by simultaneous solution with the following equation:

$$M \times V = p \quad (16-6)$$

where  $M$  = moisture, lb/cu ft, picked up by the heated air, as can be obtained by subtracting the saturation moisture content at the incoming temperature from the saturation content of the air at the final temperature

**Example.** Saturation at 80°F = 0.0013 lb/cu ft

Saturation at 32°F = 0.0003 lb/cu ft

Difference, or  $M$  = 0.001 lb/cu ft

**Regeneration.** In a similar example, Vissac also shows that the cooling of 35,000 cfm of exhaust gases by water from 120 to 60°F, will recover 31,500 Btu per min. The formula for this calculation is as follows:

$$\text{Btu} = V \times w_a \times s_a \times (T_i - T_f) \quad (16-7)$$

where the symbols are as used in Eqs. (16-4) and (16-5).

### Mechanics of Thermal Drying<sup>1</sup>

Generally speaking, when a product is desired thoroughly dry (0 per cent surface moisture) the selection of a thermal-drying unit must be made. The factors that must be taken into consideration before making the selection of a heat drier are as follows: size of coal to be dried, amount of space to be utilized, installation cost, and power requirements.

Heat driers for coal usually use a mixture of furnace flue gas and air as the drying medium. Combustion gases containing CO<sub>2</sub> in excess of 12 per cent are inert. The temperature of combustion gases is too high for coal drying if they are taken directly from the furnace. Since coal may be heated to an extent where combustion would

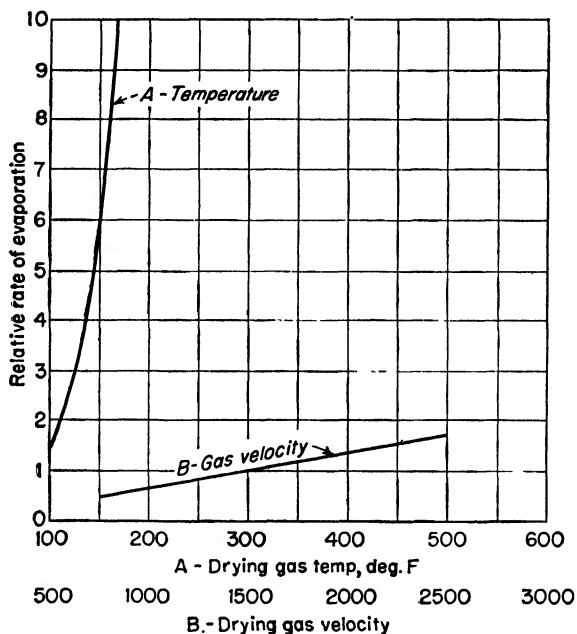


FIG. 16-5. Effect of various factors on drying rate. ("Coal Preparation," AIME.)

start, usually cold air is mixed with the flue gas to lower the temperature. The addition of air raises the oxygen content of the drying medium and increases the danger of the coal firing. In general, the coal dust will not explode if the oxygen content of the drying gases is kept below 16 per cent.

Drying gases must perform two functions: (1) evaporate the water and (2) absorb and carry off the evaporated water. The force producing evaporation is the vapor pressure at the surface of the water. Vapor pressure is defined as the pressure exerted by a body of vapor, the vapor molecules acting like those of a permanent gas.

Low-temperature drying usually is considered as being  $-212^{\circ}\text{F}$ . Since the capacity of air to take up moisture increases rapidly with increasing temperature, it is usually desirable to use high-temperature drying. Most coal driers operate at temperatures considerably above the ignition temperatures of the coal. This is possible because of the large amount of heat absorbed by the evaporation of the water.

The moisture content of a given coal varies directly, for the given sizes making up

<sup>1</sup> ROSTOSKY, A. J., and H. A. BAUMAN "Coal Preparation," pp. 600-627, AIME., New York, 1943. DRESS, L., Drying Coal Thermally and Mechanically, *Mining Congr. J.*, vol. 32, No. 6.

the coal, with the coarse sizes containing the least and the fine sizes the most. Obviously, the coarse low-moisture sizes will dry rapidly and begin to absorb heat prior to complete drying of the fine sizes present. Careful design and operation are necessary to ensure drying of the finer material without igniting or distilling off the volatile of the coarser sizes. The temperature at which the drier may be operated is dependent upon the free moisture content and the size of the coal to be dried.

The curves, according to Gill, shown in Figs. 16-5 and 16-6, illustrate the effect of various factors on the drying rate. The possibility of carrying dust and the fact that the pressure to be created by the fan varies as the square of the speed tend to modify the gains obtained from high velocity (curve *B*). The air that is circulated should be given a chance to absorb the moisture evaporated. The rapid increase in rate of

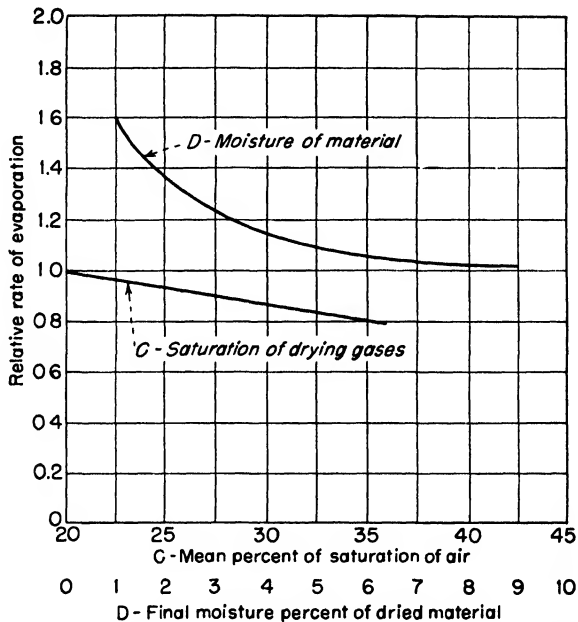


FIG. 16-6. Effect of various factors on drying rate. ("Coal Preparation," AIME.)

drying with increase in the temperature (curve *A*) of the drying medium is apparent. The temperature to which the gases are cooled is of equal importance, since with gases having high inlet temperatures the possibility of cooling below the dew point is very great. Curve *C* shows that, as the percentage of moisture in the drying gases increases, the rate of drying decreases. It is found that, during the drying of material to a very low percentage of moisture, the reduction of moisture at the beginning of the operation is very rapid. However, the reduction of moisture gradually becomes more difficult until, in drying off the last amounts of moisture, the rate of drying is comparatively slow (shown by curve *D*, Figs. 16-5 and 16-6).

The drying cycle is generally divided into two stages, as shown in Fig. 16-7.

1. **Constant-rate Period** (Fig. 16-7). During this time water is brought to the surface of the wet coal as fast as it can be evaporated. The surface remains thoroughly wet, and evaporation proceeds as from a free-water surface. A critical point is reached when the moisture coming to the surface is exceeded by the rate of evaporation from the surface.

**2. Falling-rate Period.** As the drying proceeds from the critical point, a period of uniformly falling rate is entered, which continues as long as surface moisture remains. Upon evaporation of the surface moisture, subsurface drying takes place. The diffusion of moisture becomes more difficult as the plane of water recedes. This

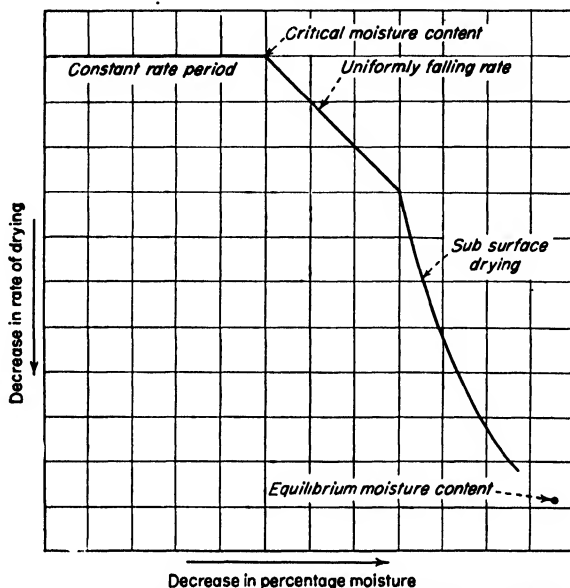


FIG. 16-7. Rate of drying. ("Coal Preparation," AIME.)

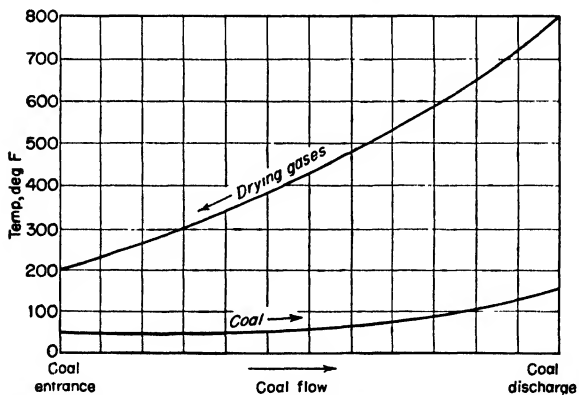


FIG. 16-8. Counterflow drying. ("Coal Preparation," AIME.)

period continues to an equilibrium point at which the vapor pressure of the moisture in the coal approaches the vapor pressure of the drying gases.

**Counterflow Driers.** Most heat driers are designed to feed the hottest gases to the hottest and driest coal. In order to do this, the hot gases are fed in at the discharge end of the drier and flow countercurrent through the material being dried. The exhaust outlet is placed at the entrance of the green coal to be dried (Fig. 16-8). In a drier of this type, the coal leaves the unit at its highest temperature; and, unless a

cooling zone is provided wherein the sensible heat of the coal is given up to preheating cold air on its way to the heating apparatus, there is a considerable loss of heat. Also, with this system, there is the risk of heating the dried coal above the ignition temperature.

**Parallel-flow Driers.** In parallel-flow driers, the drying gases at maximum temperature meet the green coal at its minimum temperature, and the gases and the coal flow together to the discharge point. With this system, a high inlet temperature can be used, since the gas is quickly tempered by coming in contact with the wet coal. The discharge temperature approaches the temperature of the dried coal, giving the coal a low exit temperature (Fig. 16-9).

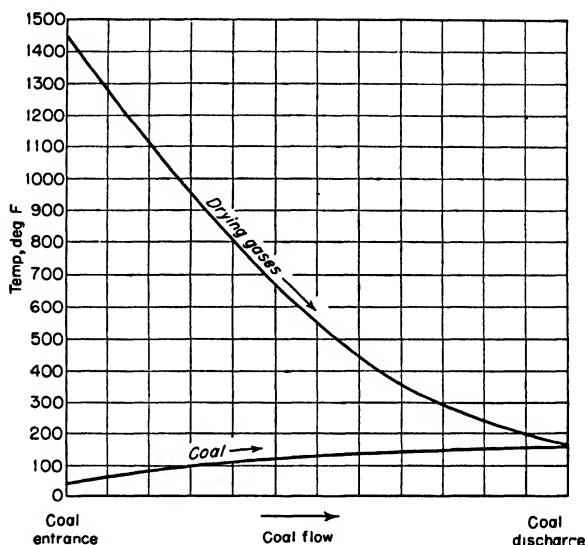


FIG. 16-9. Parallel-flow drying. ("Coal Preparation," AIME.)

### Typical Driers Available

**Rotary Driers.** Rotary driers consist of cylindrical drums pitched longitudinally approximately  $\frac{3}{8}$  in. per ft. There may be a center flue through which the hot combustion gases travel to the discharge end of the drier, where they turn and travel in reverse direction in intimate contact with the coal. The cooled wet gases are discharged through a suction fan at the feed inlet. The coal is lifted by flights and allowed to fall as the rotation proceeds, coming in contact with the partly cooled drying gases at about 600°F. The heated inner flue carries the drying gases as they cool from 1200 to 600°F. These units can handle coal as large as  $1\frac{1}{2}$ -in. top size; but, owing to degradation, 1 or  $\frac{3}{4}$  in. should be the maximum. Driers of this type require large room space and are likely to "fire" if not carefully controlled.

The **Christie drier** (Fig. 16-10) of the rotary-kiln type. The high-temperature furnace gases (1000 to 1200°F) pass around a short section of outer shell at the feed end, through nozzles to the central flue, and travel toward the discharge end. The gas enters the space between the outer shell and the flue. The hot gas then returns flowing in a direction counter to the material and is withdrawn with the moisture by an exhaust fan.

The **Roto Louvre drier** (Figs. 16-11 and 16-12) is a drum-type drier that consists primarily of an outer shell. On the inside of the shell, louver plates project radially

and are parallel with the drum. The plates overlap to form a circular inner shell that gradually increases in diameter, upon which the material is carried as it progresses through the drier. This arrangement provides longitudinal compartments or channels for the hot gases (900°F) underneath the bed of material. A full-length outlet

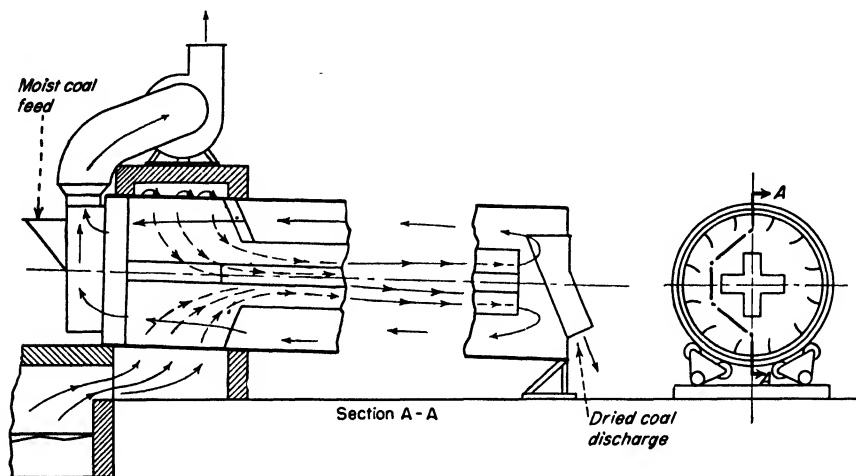


FIG. 16-10. Christie drier. Performance characteristics of two coal-dry installations. Installation A: Drier shell  $8\frac{1}{2}$  ft diam by 65 ft long, capacity 60 tons/hr,  $\frac{3}{8}$  in. to 0 washed coal, initial moisture 10 per cent, moisture dried material 3 per cent, estimated fuel consumption  $22\frac{1}{2}$  lb of 14,000 Btu coal/ton of dried material. Drier drive motor 75 hp, exhaust-fan motor 25 hp. Installation B: Drier shell  $8\frac{1}{2}$  ft diam by 70 ft long, capacity 100 tons/hr, 1 in. to 0 washed coal, initial moisture 6 per cent, moisture dried material 3 per cent, estimated fuel consumption  $13\frac{1}{2}$  lb of 14,000 Btu coal/ton of dried material. Drier drive motor 75 hp, exhaust-fan motor 25 hp. (General American Transportation Corp.)

allows the passage of hot gases into the materials by clearance between the overlapping plates or louvers, which are shaped to prevent the material from falling into the hot gas channel. Hot gases are introduced by a manifold into the channels that are only beneath the bed of coal in the slowly revolving drum.

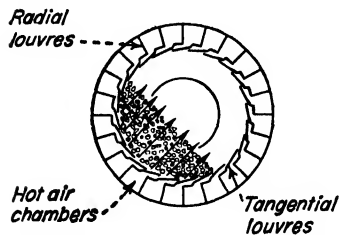


FIG. 16-11. Cross-sectional view of Roto Louvre drier illustrating flow of gases through bed of material.

**Screen and Plate Driers.** The reciprocating-screen heat driers are fundamentally quite simple. The principle is to pass high-temperature gases either up through or down through a moving bed of material on a reciprocating shaker screen. One advantage of the screen type of drier is that degradation does not present much of a problem.

**McNally-Vissac Drier.** Two dewatering actions are involved in the type of drier indicated in Figs. 16-13 and 16-14. The rapid oblique motion of the deck tends to loosen the coal bed, while the suction pressure beneath tends to compact the bed.

Controlled intermittent application of suction pressure, rather than continuous application, produces a cycle characterized by an interval during which the bed is compact, followed by an interval of relatively loose suspension. This suspended condition exists during the initial application of pressure, and hot gases flow freely down through the coal in intimate contact with all surfaces. A very rapid heat exchange

occurs, evaporating much of the external moisture of the coal. As the pressure interval continues, the bed becomes more compact, gas flow is reduced to a minimum, and free water literally is squeezed from the bed. Full advantage is taken of this squeezing action by carrying a relatively high suction pressure. This cycle is repeated many times as the coal progresses over the deck.

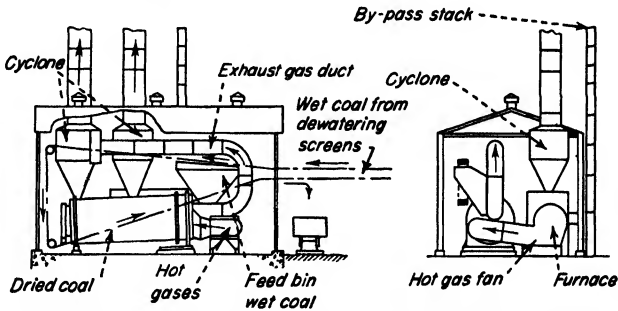


FIG. 16-12. Roto Louvre drier equipment in drying building.

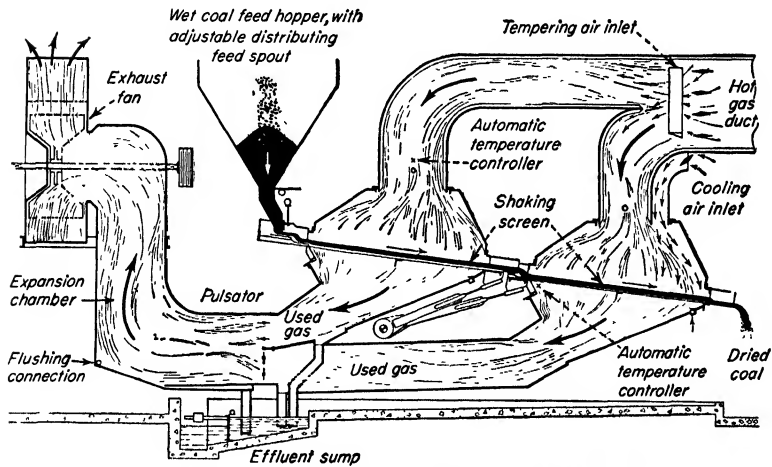


FIG. 16-13. McNally-Vissac drier. (McNally Pittsburg Mfg. Corp.)

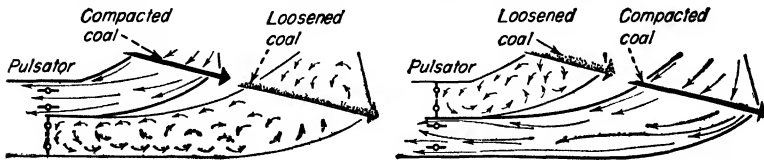


FIG. 16-14. McNally-Vissac drier pulsator action. Controlled, intermittent application of suction pressure results in a cycle characterized by an interval during which the coal bed on each screen is compacted, then loosened for the highest degree of heat transfer combined with thermal drying.

The Link-Belt SS drier comprises a drying chamber in which the drying surface is a perforated reciprocating plate. There is a hot-air inlet for gases from a coal-fired furnace and exhaust fan for drawing the hot air over the thin bed of coal, down through the perforations in the reciprocating plate to the exhaust stack. The opera-



tion of the moving element is analogous to that of the familiar shaker screen except that the perforations in the SS drier are very small and are intended only for the passing of the drying air. As the coal passes through the drier in a thin bed at slow speed, it is thoroughly dried and discharged relatively cool. Driers of this type will handle a large capacity of coarse-sized coal.

The Dwight-Lloyd Oliver drier (Fig. 16-15) operates on the principle of a straight-line perforated traveling carrier upon which rests a bed of coal through which pass the drying gases. The special traveling screens, called pallets, are designed to offer low resistance to the passage of the gases. The bed is passed through a hot-air hood with a carrier moving at a speed of 40 to 50 fpm. An exhaust fan brings heated air into the hood from the furnace and draws it through the material on the carrier at the rate of 200 to 400 cu ft per sq ft of bed area per min. The heated air enters the hood at a temperature of 400 to 700°F, being automatically regulated to a predetermined

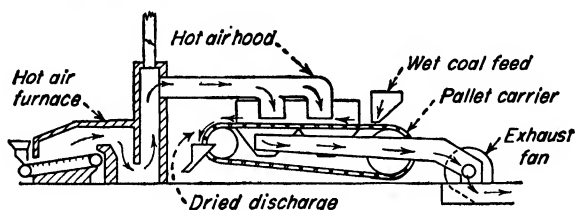


FIG. 16-15. Dwight-Lloyd Oliver drier. The wet coal is fed to the pallet carrier at the right, passes through the drying hood and drops into the dry discharge hopper at the left. The path of the drying gases is clearly shown by the arrows. (Oliver United Filters, New York.)

temperature as the conditions require. The hot air passes through the bed so rapidly that it does not overheat or burn the material being treated. After leaving the bed, the hot air leaves the outlet in a supersaturated condition at a temperature of 110 to 120°F. The fast-moving air current does more than dry by absorption; it also draws the water from the particles into the wind box below. So rapidly does the mechanical dewatering take place that streams of water run steadily from the condensate drains in the wind box.

### DRYING LOW-RANK COALS

The time required to heat particles of coal is proportional to the square of their diameter, and Parry and associates<sup>1</sup> have calculated that the probable time in minutes is equal to  $6D^2$ . In other words, a  $\frac{1}{16}$ -in. coal particle would be heated to drying temperature in 1.5 to 2.0 sec. Likewise  $\frac{1}{8}$ -in. particles should be heated in about 6 sec. Figure 16-16 shows a plot of the relationship between drying time and particle diameter, assuming an atmosphere of saturated steam or a fluidized bed.

Parry states that the net heat required to dry subbituminous coal and lignite varies from 240 to 430 Btu per lb, depending on the moisture removed, and that this heat can be obtained from 42 to 61 cu ft of hot gases at 600°F. The necessary heat also can be obtained from 7.5 to 11.0 cu ft of gas at 2000°F.

In pilot-plant drying,<sup>1</sup> over 90 per cent of the bed moisture of low-rank coal dusts was removed in a few seconds to increase the heating value of lignite by 45 per cent and of subbituminous coal by 25 per cent. One plant dried  $\frac{1}{16} \times 0$  coal dust in suspension in 1.5 to 2.0 sec with 600°F gas at a rate of 1,300 lb/hr/sq ft of column area and an efficiency of 85 per cent. A second pilot plant dried  $\frac{1}{8} \times 0$  dusts with gases at 2000°F at a rate of 1,500 lb/hr/sq ft of grate area at an efficiency of 85 to 90 per

<sup>1</sup> PARRY, V. F., J. B. GOODMAN, and E. O. WAGNER, Drying Low Rank Coals in the Entrained and Fluidized State, *Mining Trans. AIME*, April, 1949, pp. 89-98.

cent. The bulk density of the dried coal was found to be equal to that of the raw coal, making the drying process one of net heat gain.

**Nomenclature and Definitions Relating to Drying Low-rank Coals.**<sup>1</sup> Because of the considerable change in weight when low-rank coals are dried, ordinary methods of expressing the moisture removed may be confusing. For example, if a lignite containing 35 per cent moisture is dried to a product containing 5 per cent moisture, it is commonly considered, by making a simple subtraction, that the coal has lost 30 per

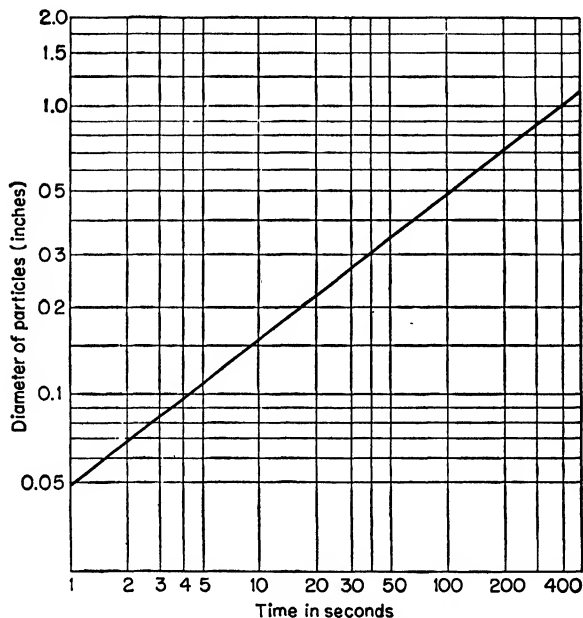


FIG. 16-16. Time required to heat particles of coal. (Parry.)

cent in weight. This is not true, and the estimating is in error by 5 per cent. The true weight loss is 31.6 per cent.<sup>2</sup> As these differences become significant when drying the low-rank coals, it is necessary to adopt a precise nomenclature for expressing results of drying. Parry and associates suggest the following for this purpose.

The improvement ratio  $R_w$  is the ratio of the weight of coal before drying to the weight after drying. If no dust or fixed gas is lost, this also expresses the ratio of heating value, volatile matter, fixed carbon, and ash after and before drying. If moisture determinations are correct, the dust lost in the system can also be calculated by comparing with the weight ratio.

$M_1$  = percentage of moisture in coal before drying

$M_2$  = percentage of moisture in coal after drying

$W_1$  = weight of coal before drying

$W_2$  = weight of coal after drying

<sup>1</sup> PARRY, V. F., and associates, *loc. cit.* Although the following was drafted by Parry and associates in conjunction with their experimental work on drying low-rank subbituminous coals and lignite, it would also apply to other ranks of coal as well.

$$^2 \text{ Loss in weight} = 100 - \frac{100 - M_1}{100 - M_2}$$

where  $M_1$  = original moisture, per cent

$M_2$  = final moisture, per cent

$$R_w = \text{improvement ratio} = \frac{W_1}{W_2}$$

$$R_m = \text{improvement ratio} = \frac{100 - M_2}{100 - M_1}$$

$$R_v = \text{improvement ratio} = \frac{\text{volatile content after drying}}{\text{volatile content before drying}}$$

$$R_c = \text{improvement ratio} = \frac{\text{fixed carbon after drying}}{\text{fixed carbon before drying}}$$

$$R_a = \text{improvement ratio} = \frac{\text{ash content after drying}}{\text{ash content before drying}}$$

$$R_h = \text{improvement ratio} = \frac{\text{heating value after drying}}{\text{heating value before drying}}$$

$$R_w = R_m = R_v = R_c = R_a = R_h, \text{ when no dust or gas is lost}$$

$$U = \text{ultimate improvement ratio} = \frac{100}{100 - M_1} = \text{maximum improvement by extracting all moisture without liberation of fixed gases}$$

$$D = \text{per cent of drying} = \frac{U(R - 1)100}{R(U - 1)} = \left(1 - \frac{M_2}{R_m M_1}\right) 100$$

= the percentage of total water in the raw coal removed during the drying process

$$M_2 = 100 - R(100 - M_1)$$

$$X = \text{lb moisture removed/lb original coal} = 1 - \frac{1}{R}$$

$$\text{Loss in weight of coal} = 100 - \frac{100 - M_1}{100 - M_2}$$

$$L = \text{dust loss, percentage of dried coal} = \left(1 - \frac{R_m}{R_w}\right) 100$$

**Economic Significance of Drying Low-rank Coal at the Mine.**<sup>1</sup> The utilization value of low-grade coals improves greatly if they are dried. This can be illustrated by an example on a Wyoming subbituminous coal, which may be assumed to have the before- and after-drying analyses and utilization properties of Table 16-13.

This table indicates that raw coal can be burned at an efficiency approaching 79.8 per cent but that the dried-coal burning efficiency may reach 84.1 per cent. From a utilization point, 1.5 tons of raw coal will be required to generate the same useful heat as can be obtained from 1.0 ton of dried coal. The economic significance of the above facts, considering the low cost of drying coal, is illustrated by the example in Table 16-14, which assumes that both coals are shipped on a freight rate of \$3.50 per ton.

The potential savings in cost of delivered heat will increase considerably as the freight rate increases. The relationship of freight rate to cost of delivered heat is as shown in Fig. 16-17. It is shown that savings of about 24 per cent are possible when the freight rate is \$5.00 per ton. The data developed in this figure are based on the assumption that freight rates remain constant on a tonnage basis and that the distribution of dried coal will not be penalized by increased rates based on heating value.

It is shown in Fig. 16-17 that the cost of drying<sup>2</sup> will about balance the freight when the freight rate is 60 cents per ton. However, because of advantages to be gained from the utilization of dried fuels, it may pay to dry such coal at destination, especially for cement mills which require dry coal, and possibly for power plants where increased efficiency and higher capacity can be obtained by operating on dried coal. A steam

<sup>1</sup> PARRY, V. F., and E. O. WAGNER, "Up-grading Missouri Basin Coals by Flash Drying," U.S. Bureau of Mines (for presentation at Colorado School of Mines, October, 1949).

<sup>2</sup> Drying costs used refer to flash drying, as described by Parry and Wagner in the section on Coal Drying.

plant operating on raw lignite is limited in capacity because of the relatively slow rate of heat release due to moisture in the coal. The capacity of such plants can be increased 15 to 20 per cent by operation on dried pulverized coal.

The cost of shipping dried coal dusts

**Table 16-13. Comparison of Raw and Dried Coal from Economic Angles<sup>1</sup>**  
(Wyoming subbituminous coal)

	Raw coal	Dried coal
<b>Proximate analysis:</b>		
Moisture, per cent . .	31 0	2 0
Volatile matter, per cent . .	30 6	43 5
Fixed carbon, per cent .	31 8	45 2
Ash, per cent .	6 6	9 3
<b>Ultimate analysis:</b>		
Hydrogen, per cent . .	6 8	5 0
Carbon, per cent .	46 4	65 8
Oxygen, per cent .	39 1	18 3
Nitrogen, per cent .	0 6	0 9
Sulphur, per cent . .	0 5	0 7
Ash, per cent .	6 6	9 3
Btu/lb, gross	8 060	11,460
Btu/lb, net	7,440	11,000
Available heat, Btu/lb, when burned with 30 per cent excess air and 500°F exit temp	6,430	9,635
Theoretical flame temp, deg F	2,880	3,110
Utilization factor	0 798	0 841
Utilization ratio	1 50	1 00

<sup>1</sup> PARRY, V. F., and E. O. WAGNER, "Up-grading Missouri Basin Coals by Flash Drying," U.S. Bureau of Mines, 1949.

**Table 16-14. Example of Economic Significance of Drying Coal<sup>1</sup>**

	Raw coal	Dried coal
Available heat, Btu/lb	6,430	9,635
Tons shipped . . . . .	1.5	1.0
Available heat shipped, million Btu . .	19 27	19.27
Tons of coal dried .	.	1 42
Cost of raw coal at mine	\$1 88	\$1.78
Cost of drying .	.	0 42
Freight at \$3.50 per ton	5 26	3.50
Total cost of 19.27 million Btu Delivered cost, cents/million Btu . .	7 14	5.70
Savings over raw coal, cents/million Btu . .	.	37.0
Savings over raw coal, cents/million Btu . .	.	7.5
Saving over raw coal, per cent . . .	.	20.3

<sup>1</sup> PARRY, V. F., and E. O. WAGNER, "Up-grading Missouri Basin Coals by Flash Drying," U.S. Bureau of Mines, 1949.

may be somewhat higher than the cost for raw coal shipped in standard equipment because the dried dust may require special handling to prevent combustion and wind losses. This factor has not been included in the savings shown and discussed.

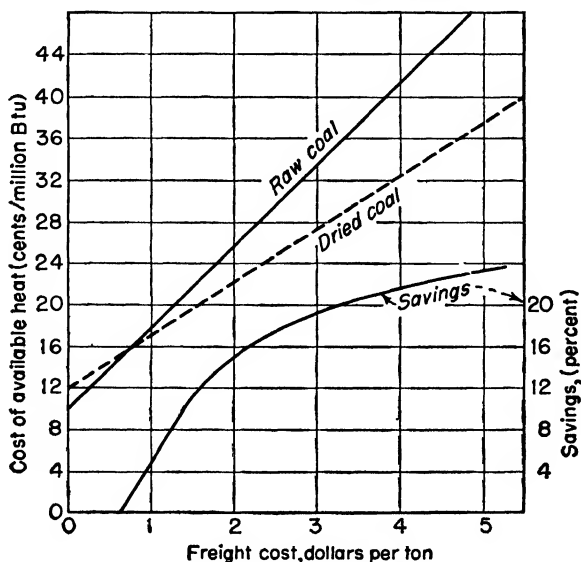


FIG. 16-17. Cost of delivered heat from subbituminous coal. (Parry and Wagner.)

**General Factors of Plant Design.** The preliminary planning of a coal-drying plant is the most essential part in the general planning of the whole coal-preparation plant; in some cases it may be the dominating factor in the selection of the cleaning methods and apparatus.

The first step is to determine all factors required for the proper design of the complete drying plant; from the "drying characteristics" of the sizes of coal to be dried within definite moisture contents must be deduced the "time element" of each phase of drying, from which, by proper reference, can be determined the number, sizes, and capacities of the driers required.

Generally speaking, most driers can be mechanically adapted to the drying of fine coals; but their efficiency will depend upon their ability to ensure the best possible contact between the coal and the hot gases.

Predrying of bulk raw coal to condition it for a dry-cleaning plant, or for preliminary dedusting, will require special types of driers to minimize degradation.

Drying of wet treated bulk coal will require a selective type of drier; as an illustration, in the same feed the large sizes may have a drying factor of 5, the small sizes a factor of 20. Unless the drier is adapted to retain the small sizes four times longer than the large sizes, the drying will not be uniform and may prove entirely inadequate. In this case also the mechanical features of the drier must avoid degradation.

In all cases where substantial outputs are required, driers with the largest unit capacity will be the cheapest to install and operate. The cost of the drier itself may be only from 10 to 20 per cent of the total cost of the drying plant; thus, the more driers, the more conveyors, elevators, fans, etc.

#### Flash Drying of Fine Coal<sup>1</sup>

For several years, the U.S. Bureau of Mines has studied the technical and economic phases of the drying of low-rank coals. Now, as a result of the operation of a flash-drying pilot plant, they state that it has demonstrated the probable success of a low-cost process for removing moisture from fine coal.

The new flash-drying process, developed by the Bureau of Mines, treats fine coal of  $\frac{1}{4}$  by 0 in. size and removes up to 95 per cent of the moisture. The cost of such drying plants is estimated to be \$100 to \$150 per ton of daily capacity, and it is estimated that total cost of drying will be about \$1.00 per ton of water removed. In large plants it is indicated that the cost of drying will not exceed \$0.75 per ton of water removed.

**Description of Operation.** Fine coal up to  $\frac{1}{4}$  by 0 in. size is drawn into the feeding system pneumatically. This system holds 6,000 lb and is pressurized. A screw feeder moves the coal into a  $1\frac{1}{4}$  in. transfer pipe, where it is picked up by a jet of inert gas under pressure and is transferred to the drying unit. The drying unit is heated by combustion of a mixture of gas, air, and products of combustion adjusted in proportion to yield the desired temperature. Most of the experimental work has been done with a theoretical flame temperature of about 2300°F. The hot products of combustion pass through a grid into the drying column and mix with the incoming coal. A light-phase fluidized bed is established in the drying column, where the heat exchange between hot gas and wet coal is extremely rapid. The fine coal moves upward with the gas and is carried vertically to the primary separator. Moisture vapor and spent hot gases move out of the primary separator into a cyclone separator, and the gases go to waste. Part of the products of combustion are brought back into the system for tempering the primary combustion mixture. The combustion system operates on about 3 per cent excess air, which permits little oxygen in the drying column.

<sup>1</sup> PARRY, V. F., and E. O. WAGNER, "Up-grading Missouri Basin Coals by Flash Drying," U.S. Bureau of Mines (for presentation at the Colorado School of Mines, October, 1949). Quoted by permission.

**Operating Results.** Five tests have been made while treating coals ranging in moisture from 24 to 60 per cent. The detailed results of these are not yet available, but Table 16-15 gives a summary of operating results and data for a typical Colorado subbituminous coal.

Coal was charged at a rate of 1,682 lb per hr, equivalent to 2,143 lb/hr/sq ft. Moisture was reduced from 27.4 to 4.3 per cent. Eighty-eight per cent of the total moisture in the coal was removed; an even greater percentage could be removed by

**Table 16-15. Operating Results from Flash-type-drying Pilot Plant<sup>1</sup>**  
(As operated on Colorado subbituminous coal)

Coal-charging rate, lb/hr	1,682
Coal-charging rate, lb/hr/sq ft	2,143
Inert gas used for moving coal, cu ft/lb	1.4
Moisture in raw coal, per cent as charged	27.4
Moisture in dried coal, per cent	4.3
Dry coal recovered, total lb/hr	1,273
Improvement ratio by weight loss	1.321
Improvement ratio by moisture determination	1.318
Ultimate improvement ratio	1.377
Degree of drying, per cent	88.1
Dust loss, per cent	0.24
<b>Heating-system data</b>	
Natural gas used, cfh	760
Net heat supplied, thousand Btu/hr	669
Air used with gas, cfh	7,584
Net heat supplied/lb of raw coal	398
Hot gas used to dry coal, cu ft/lb	9.1
Products of combustion recirculated, cfh	4,686
<b>Analysis of gases leaving column:</b>	
Water, per cent	41.9
Carbon dioxide, per cent	6.4
Oxygen, per cent	0.8
Nitrogen, per cent	50.9
Mass velocity in column, lb/hr/sq ft	2,010
Mean space velocity in column, fps	14.6
Contact time of coal, sec (max)	23.0
Pressure drop through drying column, in. H <sub>2</sub> O	2.6
Pressure in combustion chamber, in. H <sub>2</sub> O	17.5
Pressure at base of drying column, in. H <sub>2</sub> O	11.6
Pressure at top of drying column, in. H <sub>2</sub> O	9.0
Pressure at outlet of primary separator, in. H <sub>2</sub> O	5.5
<b>Temperatures in system, deg F</b>	
Combustion chamber	1080
Bottom of column	450
Top of column	285
Coal from separator	265
Gas outlet from separator	240
Gas outlet from secondary separator	235
<b>Heat balance</b>	
Net heat used, Btu/lb raw coal (excluding radiation)	363
Net heat required to dry coal, Btu/lb raw coal (includes coal carrier)	327
Drying efficiency excluding radiation, per cent	90.1
Over-all efficiency, per cent (includes radiation)	82.2

<sup>1</sup> PARRY, V. F., and E. O. WAGNER, "Up-grading Missouri Basin Coals by Flash Drying," U.S. Bureau of Mines, October, 1949.

adjusting the heat input or the coal-charging rate. If necessary, all the moisture can be removed by slowing up the process.

The temperature developed in the combustion chamber was indicated to be 2080°F, but the true flame temperature calculated from the combustible mixture was about 2300°F. The net heat required to dry the coal was calculated to be 327 Btu per lb, including the heat necessary to raise the carrier gases to 285°F, the temperature at the top of the drying column. The net heat supplied in the natural gas was 398 Btu per lb coal, giving an over-all efficiency of 82.2 per cent and efficiency excluding radiation 90.1 per cent.

The velocity of the gases and vapors near the top of the drying column was calculated to be 14.6 fps. This produces a light-phase semifluidized bed which is estimated to have a density of approximately 2.3 lb per cu ft, calculated from the differential pressure through the bed. The time of residence of the larger particles of coal is calculated from the foregoing data to be approximately 23 sec. The time of residence of the very fine particles carried with little slippage by the hot gases is approximately  $\frac{1}{2}$  sec at the operating space velocity.

The operating results in this test show that the critical space velocity was approached and the minimum time for drying the  $\frac{3}{16}$  by 0 in. particles was about

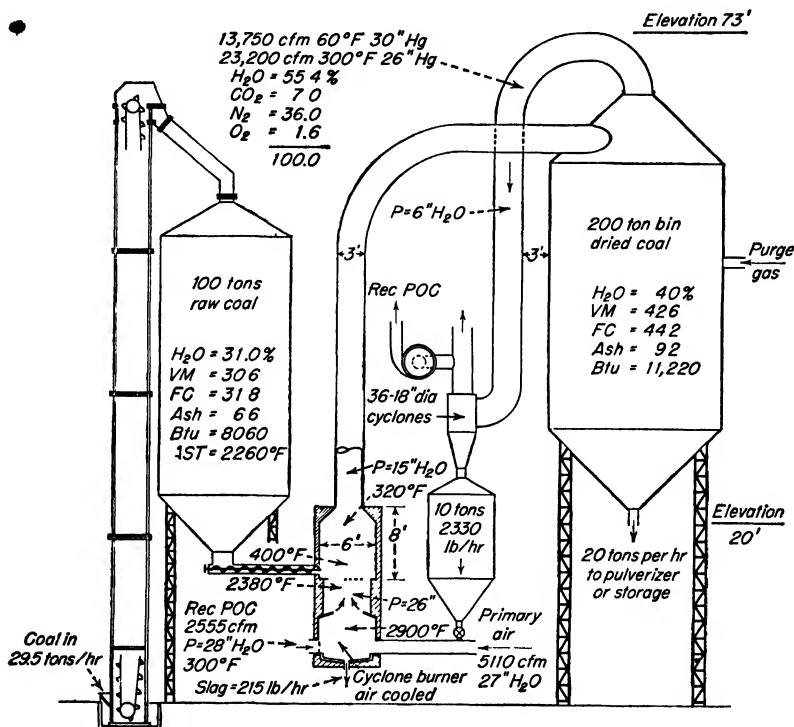


FIG. 16-18. Schematic design of drying unit for subbituminous coal. Capacity, 20 tons of dried coal per hour. (Parry and Wagner.)

reached. If the drier had been adjusted to operate at a higher velocity in this instance, less water would have been removed from the coal.

**Interpretation of Results.** For a given size of coal there is a critical space velocity, which, if exceeded, will reduce the per cent of drying of low-rank coals. The space velocity can be increased as the coal size is decreased so the coal-drying capacity can thus be increased. The capacity is also related almost directly to the temperature of the initial hot gases. When operating at space velocities less than critical, the capacity is directly proportional to the space velocity and inversely proportional to the moisture in the coal. A correlation of experimental data with the theoretical analysis indicated the following empirical formula will express the capacity of a drying column excluding radiation:

**Capacity Equation for Flash Drying.**

$$\text{Capacity, lb/hr/sq ft} = \frac{3.2(SV)T^{0.98}}{M}$$

where  $SV$  = space rate or velocity of gases in column at 300°F and 30 in. Hg ( $SV$  in fps, column considered empty, and gases include moisture evaporated from the coal)

$T$  = temperature of the hot gases, deg F

$M$  = percentage of moisture in the raw coal

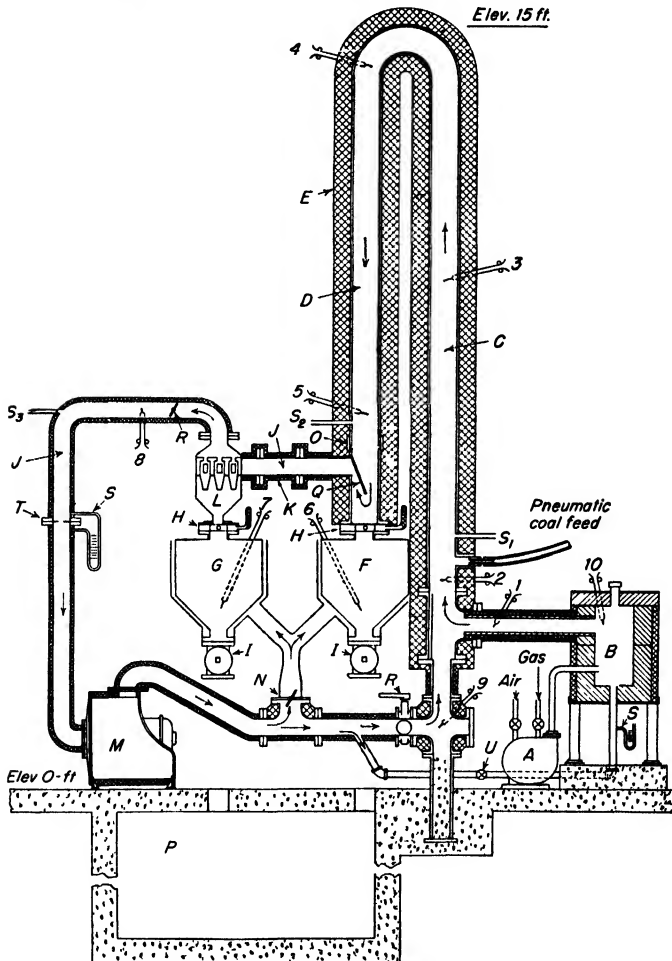


FIG. 16-19. Flash drier for fine coal.

**Design of a Commercial Plant.** Figure 16-18 shows a schematic design for a commercial drying plant, based on pilot-plant operation but designed for coal firing, instead of natural gas.

The probable operation of the unit, when drying a Wyoming subbituminous coal, is as marked. This unit will process coal of 31 per cent moisture content at a rate of



about 30 tons per hr and will deliver approximately 20 tons of dried coal per hr to a pulverizer or to storage. Some work will be required to develop a suitable hot-gas generator, but Parry feels that it should work about as outlined in the drying section.

It is estimated that a plant of this size would cost approximately \$90,000, which is equivalent to \$125 per ton of daily capacity. The total cost of drying in this unit is estimated to be 30 cents per ton of raw coal (31 per cent moisture), but in larger plants the cost will be in the range of 15 to 20 cents per ton when lignite costs \$1.25 at the mine.

The **Raymond flash drier** is used primarily for drying the fine sizes of coal. The hot gas (1000 to 1400°F) is drawn into the system by a fan connecting to the cyclone collector vent. The coal to be dried is continuously introduced into the hot gas stream by a mixer. The dry-coal- and moisture-laden gas is drawn into the cyclone collector. The dry coal drops to the bottom of the collector, and the moisture-laden gases are discharged by the fan to the atmosphere.

## CHAPTER 17

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### THE CRUSHING AND PULVERIZATION OF COAL

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## THE CRUSHING OF COAL

### COAL CRUSHERS<sup>1</sup>

Steam-plant coal-handling systems require some form of crusher for the reduction of lumps for pulverizers and stokers. The reduction is effected in a variety of methods: crushing between rolls or a roll and plate, swinging hammers, or gravity impact in a rotating drum.

#### Advantages and Disadvantages of Crushers

Advantages of crushers include:

1. Sized or crushed coal for stoker firing promotes more complete combustion and hence higher efficiency.
2. Crushed coal is more easily handled in chutes and spouts and in some types of coal-handling equipment.
3. Some types of coal crushers eliminate foreign matter such as tramp iron.
4. Plants purchasing sized coal in some cases can economically use a crusher as a stand-by. When run-of-mine coal drops below a certain predetermined price, it is purchased instead of sized coal. When the run-of-mine price rises, the crusher is bypassed and the sized coal is used. This stand-by crusher acts as insurance in case the source of sized coal breaks down and only run-of-mine is available.

Disadvantages of crushers include:

1. Some types produce degradation and fines
2. Some types, because of safety features, momentarily pass larger lumps than desired.

#### Specifying Crushers

**Specified Capacities.** Certain factors must be taken into consideration. Incoming coal may range from dust or undersized up to large lumps. Often it is possible to screen out and by-pass the undersized, sending through the crusher only the material that needs crushing. Manufacturers' tables give the largest lump each size of crusher digests, which may lead to a needlessly large crusher if the largest lump is the exceptional one. Often it is possible without undue hardship to break the exceptional lump on a grizzly ahead of the crusher.

**Purchaser's Specifications.** The purchaser must specify what coal he intends to use. Exhaustive tests have determined the Hardgrove grindability index for a great many coals. The manufacturer of the crusher can select the proper unit from the customer's coal specifications. Coals vary in hardness (see Table 17-5). He must also specify whether the crushed-coal lump size is ring size (size of ring through the lump size will pass) or square size (see Table 17-5).

Occasionally the purchaser's specifications call for a product with no lumps greater than a certain size. This is not objectionable to the breaker or the hammer mill because all the coal passes through a screen or a grid. However, it is difficult for a roll crusher to meet this requirement because an occasional large lump passes, either when there are momentary gaps between the teeth or when the release acts to pass a hard piece. Manufacturers therefore require in their specifications that 85 to 90 per cent will not be larger than the specified size.

**Feeders.** Crushers cannot control the rate at which the coal is fed to them; therefore, unless a conveyor fixes the rate, a feeder is necessary. The reciprocating feeder

<sup>1</sup> HUDSON, WILBUR G., *What Power Engineers Should Know about Crushers and Crushing*, *Power*, vol. 89, No. 10. pp. 84-86, 1945.

has the disadvantage of having pulsating flow; two feeders working alternately provide a more even flow. An apron feeder provides a more continuous flow and also seems to distribute the lumps along the moving mass on the apron. For description and capacities, see Coal Handling in Chap. 18. Whatever the type of feeder, it must stop promptly if the crusher stops.

**Installation Layouts.** The roll crusher and the hammer mill are subjected to severe working conditions. When making the layout for their installation, consider carefully how to make repairs without extensive dismantling. Provide ample clearance and headroom to maintain the equipment.

Steam-plant requirements may call for the **elimination of all metallic fragments** from the coal. A roll crusher may be provided with a magnetic pulley on the feeder belt at its discharge end, but this removes only the iron or steel. The Bradford breaker removes magnetic or nonmagnetic fragments unless they are small enough to pass through the screen openings, and it also removes large pieces of wood, straw, rags, etc. A hammer mill also traps out metal fragments, whether magnetic or nonmagnetic.

**Table 17-1. Comparison of Crusher Types**

	Roll crusher	Hammer	Bradford breaker
Low-limit product size, in	1¼-1½	¾-¾	¾
Max feed size, in. <sup>a</sup> . . .	Single row, 24; double row, 20	24	Max run-of-mine lumps
Degradation . . . . .	Less than hammer mill	Highest	Very low
Product oversize, per cent . . . . .	15-20	5-10	None
Elimination of foreign material	Requires auxiliary magnetic equipment for iron only; other refuse passes through	Integral tramp-iron pocket	Automatic removal of all foreign material larger than perforations
Wet-coal handling	No difficulty	Occasional seasonal difficulties only with smallest size	No difficulty
Capacity reduction when handling hard coals	Min	Medium	Max
Coal types . . . . .	All types	All types	Bituminous
Usual application . . . . .	Industrial plants, coal breakers	Industrial plants, central stations	Large industrial plants, central stations
Initial installation cost	Lowest	Slightly higher than roll	Highest
Maintenance cost . . . .	Low	Low	Least
Bin and chute flowability of product	Excellent	Fair because of smaller product size	Excellent

<sup>a</sup> For largest units.

### Roll Crushers

The roll crusher is fabricated in two general types, the single roll and the double roll. The **single-roll** action is secured by a toothed roll crushing the coal against a breaker plate (Fig. 17-1). As a protection to the crusher, the adjustable breaker-plate rods are provided with relief springs. When an unbreakable lump or a piece of tramp iron enters the breaker and engages the roll, the spring allows the breaker plate to swing open and pass the unbreakable material, after which the breaker plate swings back. The crusher roll and the breaker plate are provided with renewable wearing surfaces. The size of coal can be changed during operation by shifting the position of the breaker plate.

Table 17-2 shows the capacity range in tons per hour for single-roll coal crushers. The upper rows of capacity figures apply when two-thirds of the coal to be crushed is

larger than 3-in. ring size. The lower rows apply when two-thirds of the coal is already under 3-in. ring size. All capacities are based on run-of-mine coal, from which none of the smaller sizes have been removed. "Size of product," in the table, means average results, 80 to 90 per cent to pass through size of screen or ring listed.

For coal from which the smaller sizes have already been screened out, the capacity

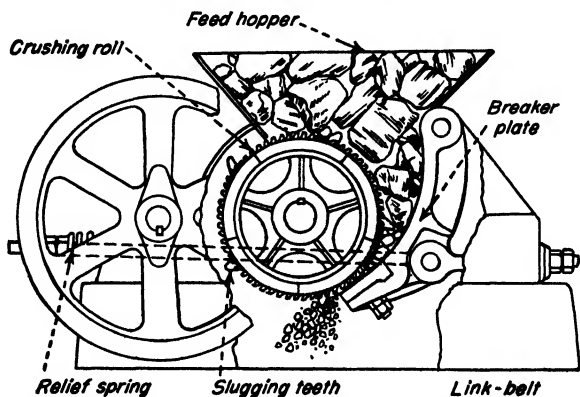


FIG. 17-1. Single-roll coal crusher. The slugging teeth give a two-stage operation. They reach up over the smaller teeth and help to break up the larger lumps so that the material can get down to the smaller teeth.

of crusher should be determined by adding together the tons of coal removed and the tons remaining to be crushed. Listed crusher capacities are based on the total tonnage as ordinarily handled, large and small together.

The double-roll action is secured by crushing the coal between two toothed rolls (Fig. 17-2). To prevent smashing the roll when unbreakable foreign material passes into the rolls, one of the rolls is provided with a spring return. The foreign material

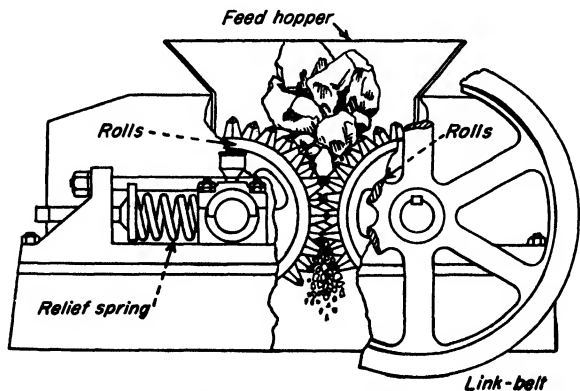


FIG. 17-2. Two-roll spring-relief coal crusher.

springs out the roll, passing the obstruction, at which the roll quickly moves back into its operating position. Modern designs of the two-roll crusher permit size adjustment during operation.

Table 17-5 indicates the normal range, in tons per hour, for which two-roll crushers are suitable, when the rolls are driven at standard speed, in handling the grade of

**Table 17-2. Single-roll Crusher-capacity Range<sup>1</sup>**  
(In tons/hour)

Min size of motor, hp		10		10		15		15		20		25		25		30									
Rpm of roll		Std	Max	Std	Max	Std	Max	Std	Max	Std	Max	Std	Max	Std	Max	Std	Max								
		60	100	60	100	60	100	50	75	50	75	50	75	50	75	50	75								
Size of crusher, in		24 × 24		24 × 30		24 × 36		30 × 24		30 × 30		30 × 36		30 × 42		30 × 54									
Size of product, in. <sup>a</sup>		Grade of coal and max size of lumps																							
Screen or ring	Cube	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"	Hard 16"	Med 20"	Soft 20"	Hard 16"	Med 20"	Soft 24"	Hard 16"	Med 20"	Soft 24"						
		10	20	25	10	25	30	15	30	40	25	35	45	30	45	50	35	55	70	45	65	85	55	80	95
1¼	¾	25	40	50	30	50	60	40	60	75	45	75	105	50	95	135	70	115	165	85	135	190	95	170	240
1½	1	15	25	30	15	30	35	20	35	45	30	45	55	35	50	60	40	65	80	65	95	115	65	95	115
1¾	1½	30	50	60	35	60	75	45	75	90	55	90	125	60	110	155	80	130	185	95	155	215	115	200	280
2	2	20	30	40	25	35	50	30	45	60	35	50	60	40	60	75	50	75	90	55	85	105	75	100	135
3	3	40	60	75	50	75	95	60	90	110	60	100	140	75	125	175	90	150	210	105	175	245	135	225	315
4	4	25	35	50	30	45	65	40	50	75	40	60	70	50	75	100	60	90	120	70	110	140	90	135	170
5	5	50	75	100	65	95	125	75	110	150	70	130	160	100	160	200	120	195	240	140	230	280	170	290	360
6	6	30	50	60	35	65	75	45	75	90	45	75	105	60	90	130	70	110	155	85	130	180	105	165	235
7	7	60	95	130	75	120	110	90	145	195	105	150	215	130	195	265	155	225	300	180	270	360	235	345	480
8	8	35	55	60	45	70	85	50	85	100	55	85	115	65	110	150	80	130	180	95	155	205	120	195	265
9	9	60	105	145	85	130	180	100	160	215	115	175	235	150	220	295	180	265	350	205	310	410	265	395	530
10	10	40	60	70	50	75	90	60	90	105	60	95	130	70	120	165	85	145	200	100	170	235	130	215	295
11	11	70	120	165	90	160	205	105	180	250	130	190	265	165	240	330	200	290	395	235	335	465	295	430	595
12	12	45	65	75	55	80	95	65	95	115	65	105	140	75	130	175	90	155	210	110	180	245	140	235	315
13	13	75	130	175	95	165	220	115	195	265	140	205	285	175	255	355	210	305	425	245	345	500	315	460	640
14	14	50	70	95	60	85	120	70	105	145	75	135	155	90	165	190	110	200	235	130	275	315	165	300	345
15	15	95	150	190	120	190	240	145	225	285	155	230	345	190	295	430	235	350	515	275	405	600	345	525	775

<sup>1</sup> Link-Belt Co.

<sup>a</sup> The "size of product" listed corresponds to the size of round screen or ring opening through which 80 to 90 per cent would pass. Capacities may be increased or decreased as much as 50 per cent by changing the speed of roll, but speeds should not exceed the maximum specified in this table. Regardless of capacity, motors should never be smaller than those shown as minimums in the table.

**Table 17-3. Horsepower per Ton of Coal Crushed per Hour<sup>1</sup>**  
(Single-roll crushers)

Type of coal	Size of product, in., screen or ring <sup>a</sup>								
	1¼	1½	1¾	2	3	4	5	6	8
Hard	2½	2½	1½	1½	1½	1½	1½	1½	1½
Medium . . .	4½	4½	2½	2½	2½	2½	2½	2½	2½
Soft . . .	1½	1½	1½	1½	1½	1½	1½	1½	1½

<sup>1</sup> Link-belt Co.

<sup>a</sup> For corresponding cube sizes, see Table 17-4.

**Table 17-4. Comparison of Square- and Round-mesh Coal Screens**

	Equivalent screen opening, in.							
Round	1½	1½	2	3	4	5	6	8
Square	1½	1½	1½	2½	3	4	4½	6

**Table 17-5. Characteristic Operating Data and Capacities for Various Sizes of Crushers<sup>1</sup>**

(Showing capacity, rpm, and motor sizes for three grades of hardness of coal)

Rpm of roll.....		130			130			120			120			115			115		
Motor hp.....		7½			10			15			15			15			20		
Size of crusher, in.		20 × 18			20 × 24			26 × 24			26 × 30			28 × 24			28 × 36		
Size of product, in. <sup>a</sup>		Grade of coal and max size of lumps																	
Screen or ring	Cube	Hard 6"	Med 8"	Soft 10"	Hard 6"	Med 8"	Soft 10"	Hard 12"	Med 14"	Soft 16"	Hard 12"	Med 14"	Soft 16"	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"
1½	1	30	40	50	40	50	60	50	65	80	65	80	100	50	65	80	80	100	120
1½	1½	35	45	55	50	60	70	60	75	90	75	95	115	60	75	90	90	110	130
2	1½	40	50	60	50	65	80	70	85	100	90	105	125	70	85	100	100	125	150
3	2	50	65	80	70	90	110	85	105	125	105	135	160	90	110	130	130	165	200
4	2¾	70	85	100	90	115	140	110	140	170	140	175	215	115	145	175	175	215	260
5	3½	.	.	.	.	.	.	140	175	210	175	220	265	145	180	215	215	270	325
6	4	.	.	.	.	.	.	.	.	.	.	.	.	170	210	250	250	315	380
8	5½	.	.	.	.	.	.	.	.	.	.	.	.	210	265	320	320	400	480

Rpm of roll ....		115			115			115			115			110			110			110		
Motor hp ....		15			20			20			25			30			40			50		
Size of crusher, in. ....		30 × 24			30 × 30			30 × 36			30 × 48			36 × 36			36 × 48			36 × 60		
Size of product, in <sup>a</sup>		Grade of coal and max size of lumps																				
Screen or ring	Cube	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"	Hard 14"	Med 16"	Soft 18"	Hard 16"	Med 18"	Soft 20"	Hard 16"	Med 18"	Soft 20"	Hard 16"	Med 18"	Soft 20"
1½	1	55	70	85	70	90	110	80	105	130	110	140	175	90	110	130	120	150	175	150	185	215
1½	1½	65	80	100	80	100	120	100	125	145	130	165	195	100	125	150	135	170	200	165	210	250
2	1½	75	90	110	95	115	135	115	140	160	150	185	215	115	145	175	155	190	230	190	240	290
3	2	100	120	140	120	150	175	145	180	210	195	235	280	150	185	220	200	250	295	250	310	365
4	2¾	125	155	190	150	195	235	185	235	285	250	315	375	195	240	290	260	320	390	325	400	480
5	3½	155	195	230	195	240	290	235	290	350	315	385	465	240	300	360	320	400	480	400	500	600
6	4	185	225	270	230	280	335	275	340	405	385	450	535	280	350	420	375	470	560	470	580	700
8	5½	225	285	345	280	355	430	340	425	515	450	570	690	355	445	535	475	590	715	590	740	890

<sup>1</sup> Link-Belt Co.

<sup>a</sup> The "size of product" listed corresponds with the size of round screen or ring opening through which 80 to 90 per cent would pass. Capacities given for two-roll Crushers are efficient capacities. Greater capacities than listed may be put through the crusher, but if this is done a larger proportion of fines will result.

bituminous coal and size of lumps shown at top of column, to turn out the "size of product" listed at the left.

All capacities are based on run-of-mine coal, from which none of the smaller sizes have been removed. "Size of product" means average results, 80 to 90 per cent to

pass through the size of screen or ring listed. When required to crush coal from which the smaller sizes have already been screened out, the capacity of crusher should be determined by adding together the tons of coal removed and the tons remaining to be crushed. Listed crusher capacities are based on the total tonnage as ordinarily handled, large and small together.

**Determination of Crusher Size.** In determining size of crusher and motor required, consideration should be given to the fact that different kinds of coal, some hard and some soft, may have to be crushed. It must also be remembered that in time the teeth of the crusher become worn, which tends to reduce capacities and increase the power required; therefore, it is well to select a crusher of generous capacity. Coal classifications are as follows:

*Hard bituminous coal*, such as West Virginia splint, Indiana block, Illinois, Iowa, Colorado, Wyoming, Pennsylvania Freeport, Kittanning, and cannel. The Hardgrove grindability ranges through 45 to 60.

*Medium-hard bituminous coal*, such as West Virginia Thacker, Panther, Banner, Coalburg, Kentucky, Harlan, Hazard No. 4, No. 7 Block and Ohio Hocking. The Hardgrove grindability ranges through 60 to 80.

*Soft bituminous coal*, such as Pocahontas, New River, Connellsville, Pittsburgh Nos. 7 and 8, and Youghiogeny. The Hardgrove grindability ranges through 80 to 105. (For more specific information on grindability of coals, refer to Tables 17-9 to 17-13.)

Performances of double- and single-roll crushers show but little difference. The single-roll design performs better on large lumps as the roll gripping action is prompter than that of the double roll. These types of crushers, properly designed, and properly selected for size, will handle any type of coal whether wet or dry.

**Limit of Size Reduction.** For roll crushers, the limit is about  $1\frac{1}{4}$  to  $1\frac{1}{2}$  in. size, because of tooth size and spacing limitations. It is possible to reduce lumps to  $\frac{3}{4}$  in. or even to  $\frac{1}{2}$  in. by using small teeth or flutes on the rolls, but with considerable loss of gripping power of the rolls.

### Hammer Mills

For fine crushing, a hammer mill (Fig. 17-3) is desirable. This unit has a single high-speed rotor equipped with pivoted hammers of varying shape according to application (triangular, bar-shaped, ring, etc.), which shatter and grind the lumps through the grid spanning the discharge opening. Spacing of the bars determines the maximum size of the product. The pivoting of the hammers provides an automatic protection when tramp iron enters the crusher; when the hammer strikes the iron, the hammer pivots away. Any material too hard to crack is thrown off centrifugally into a trap, and the hammer action grinds up such material as straw and rags which would either pass through or stall a roll crusher. Wet coal has a tendency to clog the grid openings.

Illustrated in Fig. 17-4 is a reversible-type hammer mill. The change from left- to right-hand rotation is accomplished by means of a motor switch. This alternate

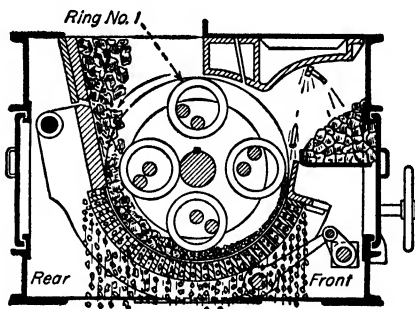


FIG. 17-3. Ring-type hammer mill. At ring No. 1, the ring takes a radial position on shaft A. At the next counter-clockwise ring the feed displaces the ring and shaft B supports and rotationally pushes the ring. Because of the radial displacement, the ring is centrifugally "off-balance," which causes the ring to press hard on the oncoming feed. (Pennsylvania Crusher Co.)



rotor rotation symmetrically sharpens the hammers, avoids shutdown for "turning hammers," and helps maintain optimum crushing surface.

**Limit of Coal-size Reduction.** The limit of size depends on the spacing of the grid bars and the hammer types which vary with the application so that the lower limits vary from  $\frac{3}{4}$  to  $\frac{1}{8}$  in.

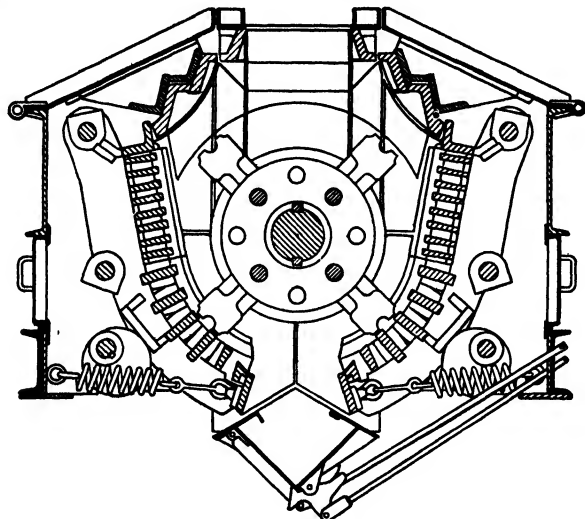


FIG. 17-4. Reversible hammer mill. The primary crushing occurs in free air as the hammer contacts the feed, projecting it at high speed against the imperforate anvil surfaces. Final reduction occurs in the zone of close cage clearances. (Pennsylvania Crusher Co.)

For further details of clearances, dimensions, and other details of the roll and hammer mills consult Link-Belt, Chicago, Ill.; Stephens-Adamson Mfg., Aurora, Ill.; Pennsylvania Crusher Co., Philadelphia, Pa.; Bartlett & Snow Co., Cleveland, Ohio; Jeffry Mfg. Co., Columbus, Ohio; and others.

### Bradford Breaker

**General Description.** Where the reduction need not be below  $\frac{3}{4}$  in., a Bradford breaker may be preferred (Fig. 17-5). This rugged slow-speed machine (25 rpm or less), with a perforated cylinder having internal baffles or lifting shelves, takes coal

Table 17-6. Capacities and Sizes of Bradford Breaker<sup>1</sup>

Size, diam × length	Motor, approx hp	Capacity, approx tons/hr	Size, diam × length	Motor, approx hp	Capacity, approx tons/hr
6' × 8'	10	40-70	10'6" × 17'	50-75	130-230
7' × 11'	15	50-100	10'6" × 19'	60-75	150-250
7' × 14'	15-20	60-125	12' × 14'	50-60	150-300
7' × 17'	20-25	80-150	12' × 17'	60-75	190-360
9' × 11'	25-30	80-150	12' × 19'	75-100	220-420
9' × 14'	30-40	100-190	12' × 22'	100-150	250-500
9' × 17'	40-50	120-230	14' × 17'	125-200	300-600
9' × 19'	50-60	130-240	14' × 22'	150-250	350-700
10'6" × 14'	50-60	110-210			

<sup>1</sup> Pennsylvania Crusher Co.

in at one end. It repeatedly lifts and drops the lumps while fines screen out and unbreakable lumps (frozen clay, tramp iron, nonmagnetic metals, rags, etc.) pass out at the other end. A reduction to about 1 by 0 in. is the usual duty of this machine, with standard capacities up to 600 tons per hr. Power requirement is comparatively low, but initial cost is more than for the roll crusher and the hammer mill, and space requirement is greater. This higher cost usually limits the application of the Bradford breaker to coal-handling systems of a minimum of 200 tons per hr. A recently developed breaker design has a modified hammer rotor within the cylinder at the refuse discharge end, which substantially increases the capacity and saves hard lumps that might not crack up by tumbling alone.

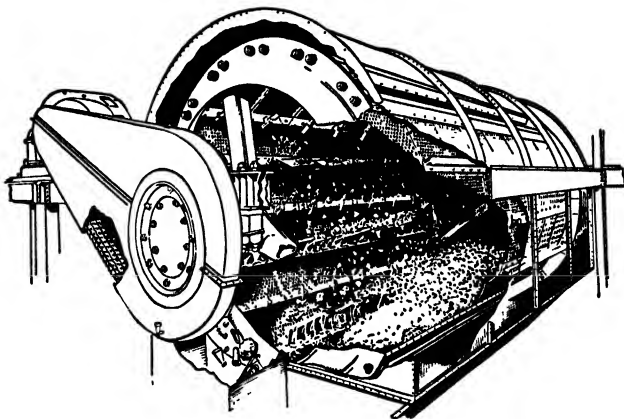


FIG. 17-5. Bradford breaker. (Pennsylvania Crusher Co.)

The Bradford breaker is best suited for large installations and central stations. Another advantage is the reduction to required size with less fines than any other type of crusher.

## THE PULVERIZATION OF COAL

### THE GRINDABILITY OF COAL<sup>1</sup>

The grindability of a coal may be arbitrarily defined in a number of ways, *e.g.*, on the basis of the calculations of the new surfaces created (Cross, Hardgrove); on the basis of the weight or percentage of the material produced passing a given sieve (Frisch and Holder); on the basis of the amount of work done to grind to a specified fineness (ball-mill); or on the basis of the actual capacities obtained in commercial pulverizers.

Unfortunately, each of these rating methods assigns quite different ranks to the same coals. The relative grindability factors depend not only on the method by which the coal is rated, but also on the coal selected as a standard of reference.

Furthermore, grindability cannot be used as a direct quantitative index of mill capacity. There are several reasons for this, a principal one being that most of the test methods are necessarily based either on batch operation, or at the most upon a considerably modified attempt at continuous operation, whereas, in practice, the continuous method of operation is usually encountered. If the performance of a pulverizer is known on only one coal of known grindability, it is not possible to predict its performance on another coal, even though the latter is of known grindability. To

<sup>1</sup> FRISCH, MARTIN, and FOSTER, Symposium on Significance of Tests of Coal, *ASTM Bull.*, vol. 37, Part II, pp. 441-466, 1937.

do this, the pulverizer must be operated as a large-scale testing machine and a sufficient number of coals of widely different grindabilities tested before its performance on untried coals can be safely predicted. Even so, the capacities as obtained from records of such tests, or from logs of daily operation, may not be directly compared

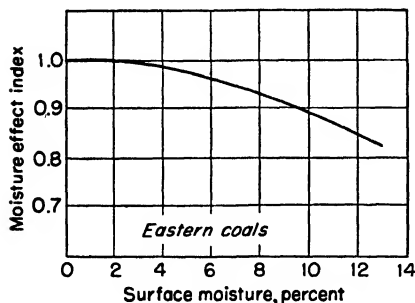


FIG. 17-6. Correction curve for effect of moisture on capacity. (ASTM, *Symposium on Significance of Tests of Coal.*)

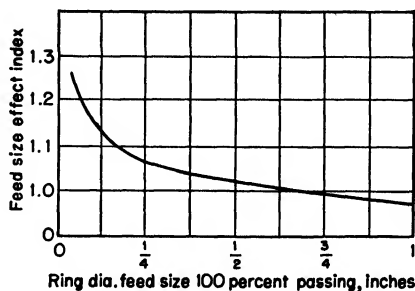


FIG. 17-7. Correction curve for effect of feed size on capacity. (ASTM, *Symposium on Significance of Tests of Coal.*)

because of differences in the moisture, feed size, or fineness of the product during the various runs. Also the physical condition of the pulverizer during each run must be considered.

However, where (1) such data include all significant items, (2) they were obtained with the pulverizer in good condition, and (3) a sufficient number of runs were obtained

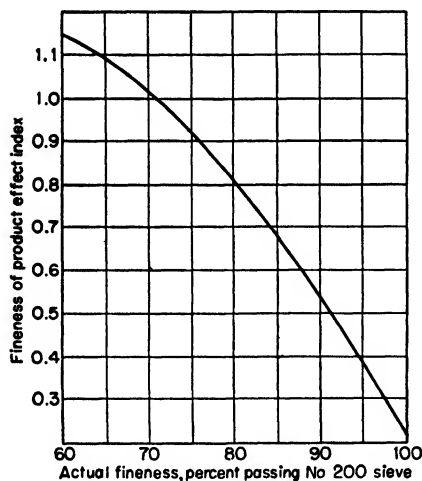


FIG. 17-8. Correction curve for effect of fineness of product on pulverizer capacity. (ASTM, *Symposium on Significance of Tests of Coal.*)

for a reliable average, it is possible to reduce all results to a standard basis of moisture, feed size, and fineness of product with sufficient accuracy to minimize the effect of these variables. The effect of the particular pulverizing characteristic of coals under consideration can then be recognized, and the coals may be ranked in accordance with the capacities obtained as corrected to standard conditions. The rankings thus obtained may be termed the grindability for the pulverizer in question. A further correlation of this grindability with those from standard test methods is also practical.

Figures 17-6 to 17-8 show typical correction curves for reducing the apparent grindability to a standard of 100 per cent passing a  $\frac{3}{4}$ -in. ring, 3 per cent surface moisture, and a fineness of product of 70 per cent through a 200 sieve. While these are of interest in indicating the magnitude of the corrections in each instance, they

are for a specific pulverizer only; for accuracy, similar curves for the pulverizer at hand should be prepared.

However, as J. F. Barkley has pointed out,<sup>1</sup> either of the tentative ASTM standard

<sup>1</sup> BARKLEY, J. F., Supervising Engineer, U.S. Bureau of Mines, in written discussion of paper.

test methods can be profitably used by coal purchasers as a guide to their selections, provided only that they fully realize that such grindability indexes are merely empirical expressions of relative grindability, subject to corrections for local conditions and use. In general, the higher the grindability number, the easier the pulverization; but, as this is relative rather than mathematical, this does not mean that a coal with a grindability 50 per cent greater than that at hand will result in a 50 per cent increase in pulverizer capacity.

#### Grindability of Coal by the Hardgrove Machine<sup>1</sup>

**Scope of Test.** A prepared sample receives a definite amount of grinding energy, and the relative grindability of coals is measured by comparing the amount of the sample that passes through a 74-micron (No. 200) sieve with a coal chosen as 100 grindability.

**Preparation and Procedure.** A representative gross sample of coal is collected and prepared in accordance with ASTM Standard Method of Sampling Coal. Only that portion of the sample is used which passes through an 1,190-micron (No. 16) sieve and stays on a 590-micron (No. 30) sieve. Of this prepared sample, 50 g is then placed in the Hardgrove grindability machine and ground until the machine makes 60 revolutions. The sample is then placed in a sieving machine over a 74-micron (No. 200) sieve. After 20 min of sieving, the material that passes through the 74-micron (No. 200) sieve is discarded and the material retained on the sieve is weighed to the nearest 0.1 g.

**Calculations of Results:** The grindability index is then calculated as follows:

$$\text{Hardgrove grindability index} = 13 + 6.93W$$

where  $W$  = weight of material passing the 74-micron (No. 200) sieve as determined from the weight of the original sample (50 g) minus the weight of the material retained on the 74-micron (No. 200) sieve

#### Grindability of Coal by the Ball-mill Method<sup>2</sup>

**Scope of Test.** The relative amounts of energy required to pulverize different coals are determined by placing a sample of coal in a ball mill and finding the number of revolutions required to grind it so that 80 per cent of the sample passes a 74-micron (No. 200) sieve.

**Preparation and Procedure.** A representative gross sample of coal is collected and prepared in accordance with ASTM Standard Method of Sampling Coal. Approximately 10 lb coal crushed to pass a 4,760-micron (No. 4) sieve constitutes the laboratory sample.

This sample is then prepared and ground through successive stages until a 500-g sample of air-dried coal sized between 1,680-micron (No. 12) and 74-micron (No. 200) sieves is obtained. This sample is then placed in the mill and ground, through a series of operations, until 400 g, or 80 per cent of the original sample passes through the 74-micron (No. 200) sieve. The end point of the test is considered as the number of revolutions of the mill required to grind exactly 80 per cent of the original sample to pass the 74-micron sieve.

**Expressing the Results.** The results are expressed as the average number of revolutions required to grind 80 per cent of the sample to pass the 74-micron (No. 200) sieve, or as follows:

$$\text{Ball-mill grindability index, per cent} = \frac{50,000}{\text{average number of revolutions}}$$

<sup>1</sup> ASTM Tentative Specification D409-37T.

<sup>2</sup> ASTM Tentative Specification D408-37T.

**Table 17-7. Principal Methods Used for Determining Grindability of Coal**  
(Bureau of Mines ball-mill and Hardgrove methods are tentative ASTM standards; others are as proposed or actually used)

Name	Type of equipment	General basis of determining index
Accepted as tentative ASTM Standards		
Ball-mill method, Bureau of Mines, ASTM D408-35T (Yancey, Furse, and Blackburn, 1934)	Special ball mill of standardized dimensions	Coal ranked in accordance with the reciprocal of the number of revolutions required to pulverize a 500-g sample in eight equal steps or cycles until 80 per cent is removed as -200-mesh material
Hardgrove (1931), ASTM D409-35T	Pulverizer of special design, rotated 60 times	Ratios of the new surface produced during a laboratory test of a coal and the new surface produced when testing an arbitrarily selected standard coal in a like manner More recently revised to specify the fineness of the Hardgrove machine product as measured by the amount passing the No. 200 sieve as the basis for grindability from the empirical equation $\text{Grindability} = G = 13 + 6.93W$ where $W$ = weight, g, of the 50-g sample passing the 200-mesh sieve
Other methods proposed or used		
Cross (1926)	Standard laboratory jar mill	Index numbers proportionate to the amount of new surface produced per unit weight of sample
Frisch and Holder (1933)	Hardgrove machine	Coals ranked in accordance with direct fineness measurements of Hardgrove machine test product as given by amount passing some one sieve as No. 300, 200, or 100. Eliminates necessity for calculating surface ratios
CIT (Carnegie Institute Technology) roll test (Sloman and Barnhart, 1935)	Roller	Consists of crushing a small sample by passing a standard roller over it 10 times
Black (1936)	Ball mill	Used samples of same volume instead of same weight for each test
FRL method (Canadian department of Mines)		Based on amount of material passing a given sieve
Baltzer and Hudson (1933)	Standard laboratory jar mill	Grindability is the amount of -100-mesh material produced in the last of 3 equal standardized cycles

**Table 17-8. Approximate Conversion Table for Hardgrove and Ball-mill Grindability Indexes**

Hardgrove grindability index		Ball-mill grindability index	Hardgrove grindability index		Ball-mill grindability index
29	20	14	90	70	52
43	30	21	100	80	60
56	40	28	110	90	70
68	50	36	118	100	89
80	60	44		110	90

NOTE: The numbers in the center column refer to the factors, either Hardgrove or ball-mill, which it is desired to convert into the other scale. If the center is considered ball-mill, the equivalent Hardgrove is on the left, and vice versa.

Table 17-9. Grindability of Bituminous Coals<sup>1</sup>

State and county	No. of samples	Range of values			Average values		
		Volatile, per cent	Ash, per cent	Grind-ability	Volatile, per cent	Ash, per cent	Grind-ability
<b>Alabama:</b>							
Bibb.....	6	33 4-36 6	7 3-12 2	51-59	35 4	8 8	54 5
Blount.....	1	.....	.....	.....	33 0	4 4	57
Jefferson.....	23	26 2-34 1	5 3-14.9	54-87	29 9	9 2	73.5
Marion.....	1	.....	.....	.....	37 6	3 4	45
Shelby.....	6	33 3-36 9	5 0-9 7	50-60	35 0	7 2	55 3
St. Clair.....	4	32.5-36.7	5 8-12 9	49-62	34 3	8 5	55
Walker.....	23	29 6-39.6	2.3-16.8	43-65	33.2	11.4	52.3
<b>Arkansas:</b>							
Franklin.....	2	15.0-15 9	10.9-11.4	99, 102	15 5	11 2	100 5
Sebastian.....	1	.....	.....	.....	16 5	15 4	100
Boulder.....	4	.....	.....	.....	61 7	10 7	43
El Paso.....	2	46.9, 68 3	7.9, 10.6	38-41	57 6	9 3	39
Fremont.....	1	.....	.....	.....	.....	.....	45
Huerfano.....	5	.....	.....	.....	37 8	12 3	44 6
Los Animas.....	2	.....	.....	44, 54	.....	.....	49
Routt.....	3	39.0-42.8	4.2-8.3	43-58	40 9	6 7	51
Weld.....	4	44 0-57 9	5.8-11.9	38-62	50 9	8 3	48 8
<b>Illinois:</b>							
Christian.....	3	.....	.....	55-59	39 1	14 3	57
Franklin.....	2	32 7, 33.4	13 4, 14 5	53-63	33 0	13 5	58
Fulton.....	5	41.6-42.8	8 3-13 3	59-68	41 9	11 7	63
Henry.....	4	40.1-44.5	10 7-21.8	60-65	42 4	14 5	62
Jackson.....	2	39 2, 42.8	5 7, 8.9	74, 75	41 0	7 3	74
Knox.....	1	.....	.....	.....	43 0	7 4	68
La Salle.....	1	.....	.....	.....	38.8	16 4	64
Macoupin.....	5	.....	.....	46-52	.....	.....	48
Madison.....	1	.....	.....	.....	.....	.....	56
Peoria.....	2	40 6, 41 3	15 5, 17 2	65, 67	41 0	16.3	66
Saline.....	1	.....	.....	53-72	37 0	9 0	60
Sangamon.....	2	37 7, 40 8	14 1, 15 6	54-68	39 2	14 8	62
St. Clair.....	4	38 5-41 1	14.9-15.0	57-62	40 4	14 9	60
Tazewell.....	1	.....	.....	.....	41 4	11 4	63
Vermilion.....	4	.....	.....	55-69	35 4	13 0	62
Will.....	7	.....	.....	58-65	43 6	10.2	61
Williamson.....	4	.....	.....	52-59	.....	.....	55
<b>Indiana:</b>							
Clay.....	2	42 7-43 2	5 6-6 2	55-56	42 9	5 9	55
Gibson.....	1	.....	.....	.....	39 3	14 5	58
Greene.....	3	41 0-46 7	10 2-13 5	60-67	43 8	11 8	63.5
Knox.....	1	.....	.....	.....	39 0	16 1	65
Pike.....	2	.....	.....	60-65	42 2	11 9	62.5
Sullivan.....	3	.....	.....	52-63	41 2	11.9	57
Vigo.....	8	38 7-43 1	6 4-11 9	58-68	40.6	9.6	62
<b>Iowa:</b>							
Boone.....	2	.....	.....	.....	.....	.....	61
Dallas.....	1	.....	.....	.....	37 8	19 9	72
Polk.....	2	39.0, 41 8	19 0, 21 0	62, 66	40 4	20 4	64
<b>Kansas:</b>							
Cherokee.....	1	.....	.....	.....	38 6	10 0	61
Crawford.....	1	.....	.....	.....	41 5	7 7	70
Linn.....	1	.....	.....	.....	31 0	2.8	70
<b>Kentucky:</b>							
Bell.....	5	34 7-39.6	4 9-7 4	42-53	37 2	6 2	49
Christian.....	2	38 1, 39.6	7 2, 7 5	51, 69	38 8	7 3	60
Floyd.....	7	37 3-41 2	5 9-11.2	44-64	38 6	7 8	53
Harlan.....	23	30 8-40 0	3 5-15 8	31-68	37 6	6.8	51
Hopkins.....	3	39.3-40 6	5.2-6.3	56-64	39.9	5 7	60
Johnson.....	2	.....	.....	57, 57	.....	.....	57
Knox.....	2	.....	.....	47, 49	.....	.....	48
Letcher.....	8	32 3-37 7	3 5-16 4	46-62	35 5	9 6	53

Table 17-9. Grindability of Bituminous Coals.<sup>1</sup> (Continued)

State and county	No. of samples	Range of values			Average values		
		Volatile, per cent	Ash, per cent	Grind-ability	Volatile, per cent	Ash, per cent	Grind-ability
Kentucky: (Continued)							
McCreary . . . . .	3	.	.	47-55	....	..	50
Muhlenberg . . . . .	2	35 9, 41 2	10 5, 16 6	74, 75	38.6	13 6	74 5
Perry . . . . .	6	33 7-34 9	7 6-15 0	43-53	.	.	.
Pike . . . . .	9	33 1-34.8	5.6-7.7	46-68	33 8	6 8	56 5
Union . . . . .	2	.....	.....	61, 66	39 0	4 0	63 5
Webster . . . . .	3	.....	.....	61-65	38 4	12 2	63
Whitely . . . . .	2	.....	.....	52-60	31.9	5 4	56
Michigan:							
Saginaw . . . . .	5	37.6-40.9	8.7-12 2	47-67	38.5	10 7	56
Missouri:							
Barton . . . . .	3	.....	.....	74-78	..	.	76
Callaway . . . . .	1	.....	.....	.	33 1	19 9	70
Henry . . . . .	1	.....	.....	.	34 6	15 5	61
Randolph . . . . .	2	35.0, 40 0	11 9, 20 4	72-75	37 5	16 2	73 5
Montana:							
Carbon . . . . .	3	36.3-39.6	9.2-17 9	47-56	38 3	13 6	51
Musselshell . . . . .	1	.....	.....	.....	35 9	11 8	56
New Mexico:							
Colfax . . . . .	1	.....	.....	.....	37 7	13 5	52
San Juan . . . . .	2	.....	.....	29-41	43 6	11 4	35
Santa Fe . . . . .	1	.....	.....	.....	8.0	17 6	36
North Dakota:							
Ward . . . . .	1	.....	.....	.....	61 7	5 4	50
Ohio:							
Athens . . . . .	5	.....	.	47-62	36 7	10 0	54
Belmont . . . . .	16	34 8-43 3	6 7-11 2	45-64	40 4	9 2	57
Guernsey . . . . .	4	35 7-37 1	4 9-10 9	49-64	36 6	8 9	55
Harrison . . . . .	3	35 2-38 4	9 4-12 0	52-67	36 8	10 7	61
Hocking . . . . .	1	.....	.....	.....	36 7	10 0	48
Jefferson . . . . .	4	34 6-37 1	11 6-12 8	54-60	35 8	12 2	57 5
Lawrence . . . . .	1	.	.	.....	41 8	9 4	51
Noble . . . . .	1	.....	.....	.....	32 2	12 8	38
Perry . . . . .	2	..	..	53, 54	....	.	53 5
Oklahoma:							
Pittsburgh . . . . .	10	29.6-31 7	11 0-17 1	47-67	30 6	14 0	57
Wagoner . . . . .	1	.....	.....	.	36 3	12 9	66
Pennsylvania:							
Allegheny . . . . .	11	33 6-37 3	7 6-11 2	52-71	34 7	9 1	62
Clearfield . . . . .	5	.....	.....	80-112	19 6	8 0	101
Elk . . . . .	2	28 6, 35 2	8 9, 9 9	67, 73	31 9	9 4	70
Fayette . . . . .	6	33 4-34 9	7.0-11 7	57-67	34 2	8 5	63
Greene . . . . .	.	.....	.....	.....	.	.	65
Indiana . . . . .	12	19 6-27 4	4 9-10 5	87-123	24 7	8 5	104
Jefferson . . . . .	9	30.6-33.3	5 7-5.7	58-99	32 0	5 7	85
Somerset . . . . .	4	.	.	94-115	17 5	9 6	103
Upper Kittanning <sup>a</sup> . . . . .	..	17 5	9 6	.....	.....	.....	.....
Washington . . . . .	8	33 6-36 8	9 1-12 5	62-70	35 4	11 2	63
Westmoreland . . . . .	15	31 2-36.1	7 7-10 4	53-90	33 7	8 8	69
Tennessee:							
Campbell . . . . .	5	.....	.....	30-54	35 8	7 3	46
Anderson . . . . .	3	35 7, 36 8	6 2 7 7	43-55	36 2	6 9	47
Claiborne . . . . .	7	37 5-40 3	5 1-9 9	47-55	38 1	6 7	50
Cumberland . . . . .	2	30 9, 34 5	7 6, 21 9	51, 72	32 7	14 8	61 5
Fentress . . . . .	4	36 8, 36 9	7.5, 13 3	48-54	36 8	10.4	51
Grundy . . . . .	2	.....	.....	50, 61	.	.	55 5
Hamilton . . . . .	1	.....	.....	.....	27 8	16 7	76
Marion . . . . .	1	.....	.....	.....	28 4	7 6	62
Morgan . . . . .	1	.	.	.....	36 5	8 3	53
Overton . . . . .	1	.....	.....	.....	.	...	64
Sequatchie . . . . .	3	.	.	.....	.	.	64
White . . . . .	1	.....	.....	.....	36 3	11 7	62

Table 17-9. Grindability of Bituminous Coals.<sup>1</sup> (Continued)

State and county	No. of samples	Range of values			Average values		
		Volatile, per cent	Ash, per cent	Grind-ability	Volatile, per cent	Ash, per cent	Grind-ability
Tennessee: (Continued)							
Maverick . . . . .	3	21 9-26 7	15 0-37 6	82-104	24 1	26 7	92
Webb . . . . .	3	40.6-50 7	8.0-29 3	32-39	44 4	17 9	36
Utah:							
Carbon . . . . .	4	41 6-44 1	5 8-6 9	43-49	42 6	6 3	45
Summit . . . . .	2	43 2, 44 1	4 6, 4 9	47, 50	43.6	4 7	48 5
Virginia:							
Buchanan . . . . .	7	30 4-35 3	3 3-5 4	58-79	32 8	3 7	70
Dickenson . . . . .	4	29 5-32 6	5 7-7 6	52-85	31.1	6 6	76 5
Lee . . . . .	9	38 4-42 7	4.1-13.5	44-50	40 4	8 6	46
Montgomery . . . . .	1	..	..	..	12 5	19.5	83
Pulaski . . . . .	3	..	..	55-63	11 7	21.4	59
Tazewell . . . . .	8	22 2-31 3	3 8-9 5	67-105	24 7	6 7	92
Wise . . . . .	5	33 6-36 0	4 0-8 0	50-78	35 1	6 2	59
Washington:							
King . . . . .	4	32 8-37 9	10 0-17 7	29-58	34 5	15 1	46
Kittitas . . . . .	3	37 7-39 6	10 5-15 8	49-52	38 3	14 0	51
Pierce . . . . .	9	21 2-36 2	9 4-18 9	67-105	29 6	13 3	83 5
Whatcom . . . . .	4	38 8-40 9	14 5-17 3	37-44	40 2	15 4	41
Thurston . . . . .	2	50 9, 57 2	10.9, 18 2	26, 34	54.0	14 5	30
West Virginia:							
Barbour . . . . .	3	..	..	62-74	39 2	8 5	66
Boone . . . . .	10	35.6-38 5	3.8-7.8	31-55	37 2	5 6	46
Braxton . . . . .	1	..	..	..	40.9	8 2	55
Brooke . . . . .	1	..	..	..	35 7	5.3	68
Fayette . . . . .	11	..	..	46-106	..	..	71
Greenbrier . . . . .	2	..	..	..	26.6	3 5	93
Harrison . . . . .	7	23 7-41 1	6 0-10 7	43-97	37 2	7 3	65
Kanawha . . . . .	20	34 8-38 8	4 9-13 6	39-71	36 4	8 4	49 5
Logan . . . . .	19	33 1-37 0	4 2-10 2	45-67	34 5	7 7	55
Marion . . . . .	5	35 4, 39 1	4 3, 9 6	49-74	37 2	6 9	62
Marshall . . . . .	1	..	..	..	38 8	6 0	44
Mercer . . . . .	1	..	..	..	17 1	..	105
McDowell . . . . .	15	17 5-23 6	5 5-10 8	69-108	19 1	7 2	97 5
Mingo . . . . .	6	30 2-38 6	5 9, 6 0	47-59	34 4	5 9	54
Monongalia . . . . .	10	35 6-38 1	9 5-11 7	56-72	37 2	4 7	64
Ohio . . . . .	2	33 0, 40 9	2 5, 3 9	54, 60	36 9	3 2	57
Preston . . . . .	4	24 4-30 5	6 4-11 1	63-107	27 8	8 1	89
Raleigh . . . . .	12	18 5-34 8	3 3-6 8	40-107	25 6	5 1	88
Randolph . . . . .	1	..	..	..	30 6	13 3	51
Taylor . . . . .	1	..	..	..	39 2	8 5	71
Tucker . . . . .	1	..	..	..	24 0	9 0	97
Webster . . . . .	3	..	..	..	35 2	6 0	61
Wyoming . . . . .	1	..	..	..	..	..	101
Wyoming:							
Campbell . . . . .	2	..	..	53, 57	67 8	10 8	55
Hot Springs . . . . .	1	..	..	..	42 8	6 3	55
Sweetwater . . . . .	6	40 0-46 9	4 4-8 9	41-76	44 1	5 9	52

<sup>1</sup> Condensed from Babcock & Wilcox Co., Grindability of Coals Mined in the United States, Canada, and Other Countries, Bull 3-241, May, 1938. ASTM Tentative Grinding Method D-409-37T.

\* This coal (Upper Kittanning, Somerset County, Pennsylvania) is the standard 100-grindability coal. The source is Jerome mine.



Table 17-10. Average Grindability and Btu Coals by Seams<sup>1</sup>

State and county	Seam	Grindability	Btu, dry	Btu, moisture- and ash-free
Alabama:				
Blount...	Altoona	57	14,670	
Bibb...	Thompson	54	13,705	
	Woodstock	53	13,890	
	Clark	59	13,890	
Jefferson...	Mary Lee	74	13,600	
	Pratt	78	14,250	
Arkansas:				
Franklin...	Denning	101		
Illinois:				
Christian...	No. 6 seam	57	..	12,300
Franklin...	No. 6 seam	56		13,100
Fulton...	No. 5 seam	64		12,000
Henry...	No. 2 seam	62		12,200
Jackson...	No. 6 seam	75		13,100
La Salle...	No. 2 seam			12,200
Saline...	No. 5 seam	59	....	13,700
Sangamon...	No. 5 seam	61	....	12,100
St. Clair...	No. 6 seam	60	....	12,600
Tazewell...	No. 5 seam	61	....	12,000
Vermilion...	No. 6 seam	63	....	12,350
Will...	No. 2 seam	60	....	12,000
Williamson...	No. 6 seam	55	....	13,300
Kentucky:				
Harlan...	Harlan	52		
Letcher...	Hazard No. 4	56		
Ohio:				
Belmont...	Pittsburgh No. 8	57		
Pennsylvania:				
Allegheny...	Pittsburgh	64		
Allegheny...	Freeport (thick)	61		
Armstrong...	Upper Freeport	57		
Cambria...	Lower Freeport	99		
	Upper Freeport	87		
	Lower Kittanning	107		
Fayette...	Pittsburgh	63		
Indiana...	Lower Kittanning	107		
Jefferson...	Lower Freeport	92		
Washington...	Pittsburgh	60		
Westmoreland...	Pittsburgh	69		
West Virginia:				
Boone...	Winifrede (Dorothy)	39		
Fayette...	No. 2 gas seam	56		
	Powelton	62		
	Sewell	95		
Greenbrier...	Sewell	93		
Harrison...	Pittsburgh	60		

<sup>1</sup> Condensed from Babcock & Wilcox Co. *Bull.* 3-241, May, 1938.Table 17-11. Grindability of Canadian Coals<sup>1</sup>

Province	No. of samples	Range of values			Average values		
		Volatile, per cent	Ash, per cent	Grindability	Volatile, per cent	Ash, per cent	Grindability
Alberta	7	22 3-58 4	11 8-20 3	40 <sup>a</sup> -130 <sup>b</sup>	35 0	19 0	101 <sup>c</sup>
British Columbia...	15	22 3-28 2	6.9-16.9	62 <sup>d</sup> -117	24 9	10 4	101 <sup>c</sup>
New Brunswick...	1				31 3	20 8	72
Nova Scotia...	7	30 9-36.3	6 0-21 7	45-74	33 9	15 2	66
Ontario <sup>e</sup> ...	1				64 3	16 7	64
Saskatchewan <sup>e</sup> ...	2	40 6, 44 1	12 6, 18 1	58, 100	42 3	15 3	
Vancouver Island	9	37 7-40.1	8 3-17 2	50-92	39 0	13 3	66

<sup>1</sup> Condensed from Babcock & Wilcox Co. *Grindability of Coals Mined in the United States, Canada, and Other Countries*, *Bull.* 3-241, May, 1938. ASTM Tentative Grinding Method D409-37T.<sup>a</sup> Only two of the seven samples in this group were below 80 grindability.<sup>b</sup> Kootenay samples tested 124 and 130 grindability.<sup>c</sup> Not including two low-grindability samples.<sup>d</sup> Only two samples in this group were below 86 grindability.<sup>e</sup> Lignite.

Table 17-12. Analyses and Grindability of Coals in Great Britain<sup>1</sup>

Source and type	Proximate analysis			Grind-ability	Ash-soften- ing temp, deg F
	Volatile, per cent	F.C., per cent	Ash, per cent		
Aberdare, dry duff	12 1	72 2	15 2	71	
Abergrave, duff...	7 9	79 6	12 5	68	
Aberpergwin, anthracite duff and billy duff...	8 9	78 8	12 4	59	
Aldridge slack, Midland district	33 9	51 1	12 0	56	2295
Allen's rough slack, Midland district	37.9	54 4	7 7	43	2310
Anthracite	.	.	.	29	
Baggeridge slack, Midland district	31 6	49 2	19 2	46	2320
Bedwas navigation colliery, rock-vein coal	23 4	53 5	23 1	64	
Bersham slack, North Wales	29 9	49 2	20 9	46	2610
Betteshanger slack, Kent district	14 1	76 3	9 6	88	
Brownhills slack, Midland district..	36 9	54 9	8 2	35	2395
Callgeidrim Breaker duff	6 5	83.5	10 0	39	
Chatterly and Whitefield slack	....	....	....	62	
Chislett	....	....	....	72	
East Cannock slack, Midland district..	32.2	48.4	19.4	58	2330
East Hetton duff, Durham district	.	....	.	60	
East Hetton duff, No. 1, Durham district	34 0	54 2	11 8	64	2200
East Hetton duff, No. 2, Durham district	29 7	51 1	19 2	61	2360
Emlyn anthracite colliery, billy duff	6 5	77 8	15 7	54	
Great Mountain, anthracite duff	6 6	80 1	13 3	43	
Hawkins slack, Midland district	28 3	49 5	22 2	44	2785
Haydock rough small, Yorkshire	36 3	57 3	6 4	47	2200
Holditch slack, Midland district	32 4	59 2	8 4	49	2125
Hollybank Mitre slack, Midland district	35 1	50 1	14 8	46	2275
Lalleshall slack, Midland district	38 8	51 9	9 3	56	2775
Littleton slack, Midland district	32 2	48 3	19 5	51	2295
Llay Main slack, North Wales	35.2	58.2	6.6	50	2410
Llay Main dust, North Wales	....	....	....	65	
Polmaise anthracite	....	....	....	79	
Primrose slack, South Wales	29.9	43 1	27 0	45	2540
Ruabon slack, North Wales	32 2	52 8	15 0	45	2480
Saltwell's slack, Midland district, Staffordshire	33.2	46.7	20.1	42	2625
Scotch anthracite duff	....	....	.	25	
Scotch coal	38 4	55 3	6 3	43	
Scotch singles (2 samples) ..	36 7	53 3	10.0	46, 49	
Snowden dry clean smalls	21 2	69 9	8 9	85	
Wallsend	42.3	53 3	4 4	57	
Walsallwood slack, Midland district, Staffordshire	34.2	42 8	23.0	56	2600
Warrens Hall slack, Midland district, Staffordshire	26.1	60 1	13 8	60	2345
Welsh anthracite, Wales (avg of 2 samples) ..	9.1	87.0	3 9	45, 69	2360
Whitburn	....	....	....	69	
Yorkshire dry slack, Yorkshire	31 9	52 7	15 4	45	2260

<sup>1</sup> Babcock & Wilcox Co., Grindability of Coals Mined in the United States, Canada, and Other Countries, *Bull.* 3-241, May, 1938. Grindability according to ASTM Tentative Standard D409-37T.

Table 17-13. Analyses and Grindability of Typical Foreign Coals by Mines<sup>1</sup>

Country, source, and type <sup>a</sup>	Proximate Analysis			Grind-ability	Ash-soften- ing temp, deg F
	Volatile, per cent	F.C., per cent	Ash, per cent		
<b>South Africa:</b>					
Coalbrook colliery, Vereeniging.....	29.6	50.4	20.0	51	2830
Ridan colliery, Vereeniging.....	31.9	51.3	16.8	47	3000
Coronation colliery, Witbank district.....	27.3	59.7	13.0	48	2940
<b>Australia:</b>					
John Darling, Borehole seam.....	35.0	55.0	10.0	65	
John Darling, Victoria seam.....	34.0	51.3	14.7	64	
Elrington.....	41.6	49.5	8.9	47	
Main Range, Lithgow seam.....	31.4	51.5	17.1	47	2935
South Clifton, Bulli seam.....	24.6	62.4	13.0	85	2250
Steel Works, Lithgow seam.....	33.1	52.5	14.4	47	3000+
Vale Ciydd No. 2, Lithgow seam.....	34.3	52.3	13.4	51	2760
Victoria.....	37.3	47.8	14.9	56	
Wontghaggie (Victoria).....	...	...	...	40	
<b>Belgium:</b>					
Coal Charbonnages de Werister.....	13.9	74.1	12.0	85	
Coal Charbonnages de Werister.....	14.3	77.4	8.3	66	
<b>Brazil:</b>					
Porto Allegro.....	29.7	40.5	29.8	49-56	
<b>Chile:</b>					
Lirquen.....	45.6	39.9	14.5	41	2170
Lota.....	41.0	51.3	7.7	40	2360
Schwager.....	41.8	52.6	5.6	47	2200
<b>China:</b>					
Kallian (Shanghai).....	38.0	34.5	27.5	67	
Fushain No. 2 (Shanghai).....	41.9	47.1	11.0	48	2790
Peipiao.....	29.3	41.8	28.9	56	
<b>Czechoslovakia:</b>					
Sofie Mine Olau Lazy.....	...	...	...	63	
Anslem Mine, Petrokive.....	16.0	73.1	10.9	88	
Bettina Mine, Dombrau.....	29.0	53.3	17.7	60	
<b>France:</b>					
Bethune.....	30.3	59.2	10.5	64	
Bruay.....	26.5	64.4	9.1	59	
Courrières.....	25.7	64.1	10.2	80	
Douges.....	23.5	65.0	11.5	85	
Drocourt.....	21.8	69.7	8.5	92	
Gouffre.....	10.3	69.2	20.5	88	
Hornu.....	24.8	49.9	25.3	92	
Maries.....	25.4	65.0	9.6	56	
Nord de Charleroi.....	11.8	70.5	17.7	112	
<b>Germany:</b>					
Anthracite (Itenzoe).....	...	...	...	39	
Blecheimer Braunkohle.....	54.8	31.7	13.5	99	2425
Eassein.....	...	...	...	85	
Victoria Augusta, Fettefein ..	...	...	...	100	
Hattingen.....	11.9	81.2	6.9	96	2260
Magerfein.....	9.0	76.3	14.7	53	
Witkowitz, Bergbau, and Eisen	17.9	69.4	12.7	53	2380
Upper Silesian slag coal.....	...	...	...	53	
Rhine colliery, Obercassel.....	...	...	...	77	
Semianthracite, Heinrich.....	...	...	...	80	
Subbituminous, Ibbenburen ..	...	...	...	93	
Subbituminous, Eschweiler.....	...	...	...	73	
Jacobi.....	...	...	...	80	
Subbituminous, Ludwig.....	...	...	...	66	
<b>German Austria:</b>					
Fohnsdorfer nut.....	...	...	...	51	
Grünbacher.....	...	...	...	72	
Statzendorfer.....	...	...	...	62	
Tauchener.....	...	...	...	30	

Table 17-13. Analyses and Grindability of Typical Foreign Coals by Mines.<sup>1</sup>  
(Continued)

Country, source, and type <sup>a</sup>	Proximate analysis			Grind-ability	Ash-soften- ing temp, deg F
	Volatile, per cent	F.C., per cent	Ash, per cent		
Holland:					
Emma . . . . .	19 7	74 7	5 6	93	2490
Wilhelmina (avg of 7) . . . . .	11 0	84 3	4 7	55-70	
India . . . . .	33 4	49 8	16 8	52	
Japan:					
Miike . . . . .	40 8	50 4	8 8	80	2095
Lignite, Naikwa . . . . .	45 4	46 4	8 2	38	
Yubari dust . . . . .	41.7	48 3	10 0	48	
Yugoslavia:					
Banja Luka (2) lignite . . . . .	41 2	36 8	22 0	59	6970 <sup>b</sup>
Breza (2) lignite . . . . .	38 5	44 9	16 5	42	8960 <sup>b</sup>
Erbskohle . . . . .	44 3	39 0	16 7	26	7560 <sup>b</sup>
Grieskohle . . . . .	47 4	32 4	20 2	22	7086 <sup>b</sup>
Kajeveja . . . . .	41 2	41 2	17 6	60	11010 <sup>b</sup>
Kakanj . . . . .	39 4	44 9	15 7	38	9950 <sup>b</sup>
Staubkohle . . . . .	41 7	35 2	23 1	28	6270 <sup>b</sup>
Valenja lignite . . . . .	45 8	29 5	24 7	33	4707 <sup>b</sup>
Zabukovag lignite . . . . .	30 9	34 3	34 8	59	6,474 <sup>b</sup>
Manchukuo (2 samples) . . . . .		...	...	46, 58	
Mexico:					
North Mexican anthracite (Coahuila) . . . . .	2 3	91.0	6.7	27	2470
New Zealand:					
Warco coal (2 samples) . . . . .	48 1	46 9	6 0	61, 65	2120
State mine, Liverpool coal . . . . .	35 8	59 8	4 4	81	2430
Newfoundland . . . . .	31 5	59 9	8 6	73	2250
Philippine Islands:					
Uhling, Cebu (avg 3 samples) . . . . .	42 3	50 7	7 0	44-52	2265
Russia:					
Bobriki . . . . .	33 0	35 8	31 2	95	
Kizal (avg 2 samples) . . . . .	29 7	44 0	26 3	50, 54	
Spain:					
Balearic Islands . . . . .		..	....	71	
Tasmania (avg 2 samples) . . . . .	35 5	50.3	14 2	37, 49	2475
Turkey (avg 2 samples) . . . . .	24 1	43 7	32 2	82, 89	

<sup>1</sup> Babcock & Wilcox Co., Grindability of Coals Mined in the United States, Canada, and Other Countries, *Bull.* 3-241, May, 1938. Grindability according to ASTM Tentative Method D409-37T.

<sup>a</sup> Designations are local, but first name usually refers to mine or colliery and second to seam or district.

<sup>b</sup> Btu as received.

### Grinding Anthracite for Pulverized Fuel<sup>1</sup>

According to C. H. Frick,<sup>1</sup> the characteristics of anthracite are considerably different from those of bituminous coal or other materials that might be ground with a vertical mill in that the coefficient of friction between the various anthracite particles is very low. As a result, the particles have a tendency to slide on each other and slide on the ball race, whereas with the horizontal mill many tons of small balls are raised by the rotation of the mill and dropped, causing thousands of hammer blows, which crush the coal to the desired fineness. In the vertical mills, the few balls, usually 12 or 15 in. in diameter, tend to slide and lose their roundness, making necessary frequent replacement and high maintenance costs; whereas in the ball-and-tube mill the small balls, generally 1¼ to 1½ in. in diameter, wear down to almost nothing, and addition is made periodically of new balls to maintain a certain level in the mill. The horizontal ball-and-tube mill is therefore the most used type of mill today for grinding anthracite.

<sup>1</sup> FRICK, C. H., Grinding of Anthracite for Pulverized Fuel, *AIME Tech. Pub.* 2061, 1946.

As was discussed in the section on anthracite volatile matter, anthracite is softest at the extreme western tip of the fields and generally becomes progressively harder as the distance to the east and northeast increases. Roughly the variation is from about 60 Hardgrove in the western end of the region to 35 in the eastern. Frick has

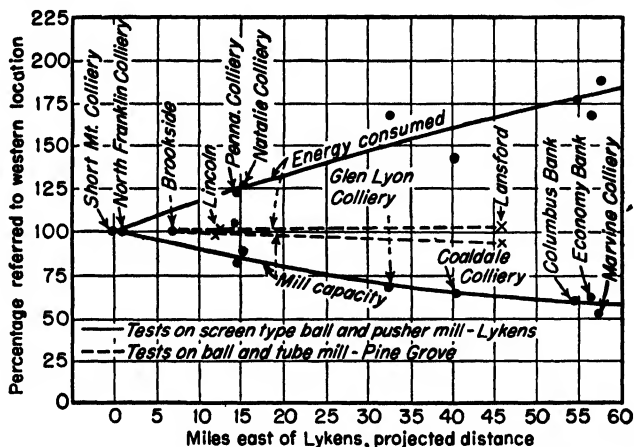


FIG. 17-9. Results of experiments with coal from various sections of the anthracite region. (C. H. Frick.)

plotted this variation for its effect on the capacity of both ball-and-pushers and ball-and-tube mills. He concludes that, whereas in the ball-and-tube mill the variation in capacity with location in the field and ash content is comparatively small, there is considerable variation in the output of the vertical mill, depending on the hardness of the coal (see Fig. 17-9).

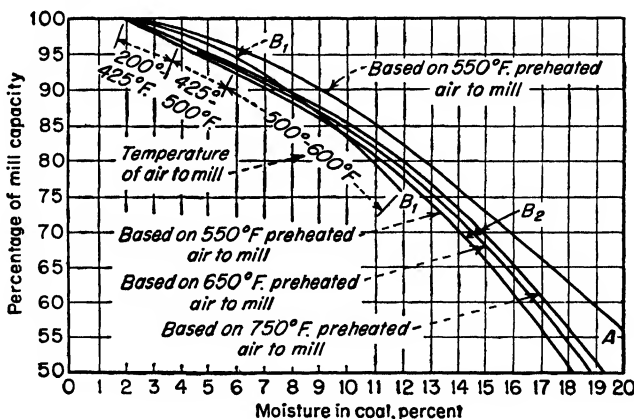


FIG. 17-10.\* Effect of moisture on capacity of horizontal ball-and-tube mill. Curves from manufacturers' proposals: Curve A from manufacturer A; curves B<sub>1</sub> and B<sub>2</sub> from manufacturer B. (Frick, C. H., *Grinding of Anthracite for Pulverized Fuel*, AIME Tech. Paper 2061, 1946.)

**Effect of Moisture Content.** The output of a given fineness with a given mill installation varies considerably with the initial moisture content of the coal entering the mill. As all anthracite is now prepared by wet processes, and as small coal has a tendency to hold its moisture for even longer than the larger sizes, this can become a

major factor in mill capacity. As an example, in the winter the moisture content of the small anthracite may be at least 20 per cent. As is shown in Fig. 17-10, even though preheated air is used in mill drying, the capacity is less than 60 per cent of

Table 17-14. Grindability of Pennsylvania Anthracite<sup>1</sup>

County	No. of samples	Range of values				Average values		
		Volatile, per cent	Ash, per cent	Ash-softening temp, deg F	Grindability	Volatile, per cent	Ash, per cent	Grindability
Carbon..	2	4.7	14.1	2950	30-33	4.7	14.1	31.5
Lackawanna	1	6.3	9.2	2900+	26	6.3	9.2	26
Luzerne	5	5.1-5.9	6.6-14.7	3000	21-34	5.5	10.5	27.5
Northumberland	7	5.9-8.6	8.3-15.5	2875-3000	44-61	6.9	10.7	49.4
Schuylkill	19	3.0-7.4	9.3-17.7	2575-2975	30-63	5.1	16.7	43.2
Lower Susquehanna River	3	7.8-7.9	17.3-20.6	1925-2610	28-33	7.8	19.2	30.3
Totals and avg	37	3.0-8.6	6.6-20.6	1925-3000	21-63	6.0	13.4	34.6
Luzerne bone <sup>a</sup>	1	5.4	46.0	2925	36	5.4	46.0	36

<sup>1</sup> Condensed from Babcock & Wilcox Co., Grindability of Coals Mined in the United States, Canada, and Other Countries, *Bull.* 3-241, May, 1938. ASTM Tentative Grinding Method D409-37T.

<sup>a</sup> Bone is material containing more than 40 per cent and less than 75 per cent carbon.

what it would be with initial moisture of less than 2 per cent. It thus usually becomes necessary to dry anthracite before it enters the mill even if preheated air is used in the mill.

Table 17-15. ASTM Standards for the Reduction of Coal Samples<sup>1</sup>

Weight of Sample to Be Divided, Lb	Largest Size Allowable in Sample before Division, In.
1,000 or over	1
500	$\frac{3}{4}$
250	$\frac{1}{2}$
125	$\frac{3}{8}$
60	$\frac{1}{4}$
30	$\frac{3}{16}$ or to pass a 4,760-micron (No. 4) sieve

<sup>1</sup> ASTM D21-16, Standard Method of Sampling Coal, ASTM Standards, 1936, Part II, p. 382.

## PULVERIZERS

Originally coal was dried<sup>1</sup> before entering the pulverizer or was fed to it in an undried condition. No heat was added to the mill system for moisture removal. Today practically all modern pulverizer installations are equipped for mill-drying.

In a direct-fired system, hot air is preferably used for drying. In addition to drying and transporting, this hot air is also the burner primary air. If hot flue or furnace gas is used directly for drying, it must be diluted with air so that the CO<sub>2</sub> content is low enough not to interfere with ignition.

Either a regenerative or a recuperative type of air heater is the best source of hot air for mill drying. If the moisture content is not too high, a small steam-air heater may be used.

<sup>1</sup> DE LORENZI, OTTO, Combustion Engineering Co., Inc., pp. 7-14, 7-17.

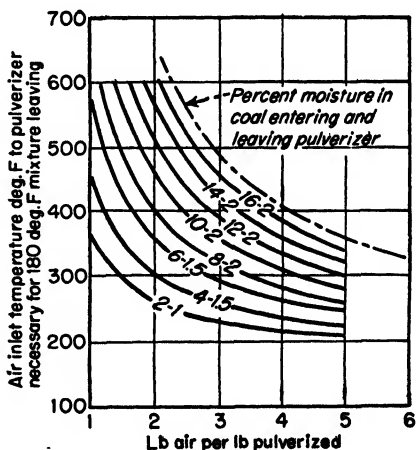


FIG. 17-11. Air quantity and temperature required for mill drying. ("Combustion Engineering," 1st ed., p. 7-16.)

For direct-fired mills the range of mill outlet temperature is most frequently between 150 and 180°F. The inlet temperatures to the pulverizers are frequently as high as 500°F, and in rare cases 600°F (Babcock & Wilcox cyclone burners use 700°F). The curves of Fig. 17-11 show the quantity and temperature of heated air required for variation in moisture content of Pittsburgh No. 8 and similar coals.

### Classification of Mills

**Mechanical mills** for pulverizing coal are usually classified according to the technique utilized to secure the desired reduction of particle size. These divisions are **ball-and-tube mill**, **ball-race mill**, **roller mill**, and **impact mill**.

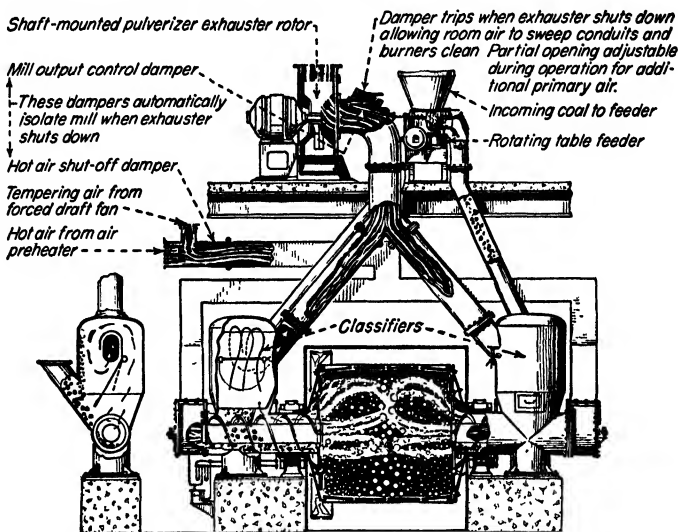


FIG. 17-12. Ball-and-tube-mill pulverizer. The rotating table feeder allows predetermined amounts of coal to drop to the spiral flights which carry the coal into the ball mill. Hot air carries the coal through the classifier, which allows only the proper sized particles to pass. (Foster Wheeler Corp.)

In addition to the widely used mechanical mills mentioned, there is also the **attrition** type, characterized by the absence of any moving parts. This type is as yet in the experimental stage with respect to the application for coal-combustion purposes.

**Ball-and-tube Mill.** This mill consists of a rotating drum charged with steel balls and coal, as indicated in Fig. 17-12. Heated air enters the mill through the central pipes and carries the pulverized coal through the annular opening to the classifier. Oversize rejects drop from the classifier to the spiral flights, where they mix with the raw-coal feed. As the rejects are practically free of moisture and preheated considerably above the ambient temperature, they tend to reduce the surface moisture of the raw coal by surface contact. The spiral flights feed the raw coal and the rejects into the mill, where they are pulverized by impact and attrition brought about by the cascading action of the balls and coal.

Feed control is automatic, so that a constant level is maintained in the mill regardless of the output. A feature of this mill is the large reserve supply of fuel maintained in the mill (resembling the bin system) that is available to meet fluctuation of demand or alleviate the effect of coal-flow interruption by hanging up in bunker or spouts.

Exhauster fans are the radial-vane type and handle both the air and the pulverized

coal. The exhausters operate at constant speed, the rate of discharge being damper-controlled. The exhausters are subject to wear due to abrasive action of the coal on the internal surface.

**Ball-race Mill.** The grinding elements of this mill consist of one stationary grinding ring, one bottom rotating ring, and a complement of large steel balls interposed between the two rings, thus forming a ball-bearing-like assembly. The raw-coal feeder deposits the coal inside the ring of balls, where it is pulverized and partly dried between the grinding elements, which are heated by the primary air as it passes through the pulverizer. The primary air entrains the fines as soon as formed, heats them, and carries them to the classifier, where oversized material is rejected and

Table 17-16. Pulverizer Comparison

	Ball-and-tube mill	Roller		Impact
		Ball-race mill	Bowl	
Metallic contact in grinding zone	Point contact of balls on liner, balls on balls	In contact	None	None
Drive	Horizontal, pinion and large gear	Vertical, bevel gears	Vertical, worm gears	Horizontal, direct coupling from motor
Tramp material	Assists grinding until ground up	Promptly rejected after initial contact with grinding elements		Unitype, magnet in feeder and tramp pocket in mill. Atrita, magnet in feeder
Size of plant	Small, medium, large	Small, medium, large	Small, medium, large	Small, medium
Loss of fineness with wear of grinding elements	None but requires ball replacement	None	Adjustment provides for constant fineness	Largest
Noise	Highest	High	Quiet	Least
Pulverizer fan	Handles coal and air	Handles clean air only	Handles coal and air	Handles coal and air
Normal type of coal	Anthracite, semi-bituminous, bituminous	Semibituminous, bituminous, lignite	Semibituminous, bituminous, lignite	Semibituminous, bituminous

returned to the grinding zone for further pulverization. Material of proper fineness is conveyed by primary air through pipes to the burner or burners. The hot dry rejects from the classifier form the recirculating load in the pulverizer and, in passing through the grinding zone, provide relatively large surface contact with the raw coal, thus providing additional drying effect.

The automatic feed control can be coordinated with any system of combustion control, as fuel is varied simply by regulating the primary-air damper. Because the feeder controller operates from the rate of air flow and pressure drop through the grinding zone, the response to load change is rapid.

The pulverizer operates under pressure, so that the primary-air fan handles only clean air, and the fan blades are not subject to the abrasive action of pulverized mate-



rial. This system makes it possible to use fans of higher efficiency and provides more effective distribution of pulverized coal to the burners (Fig. 17-13).

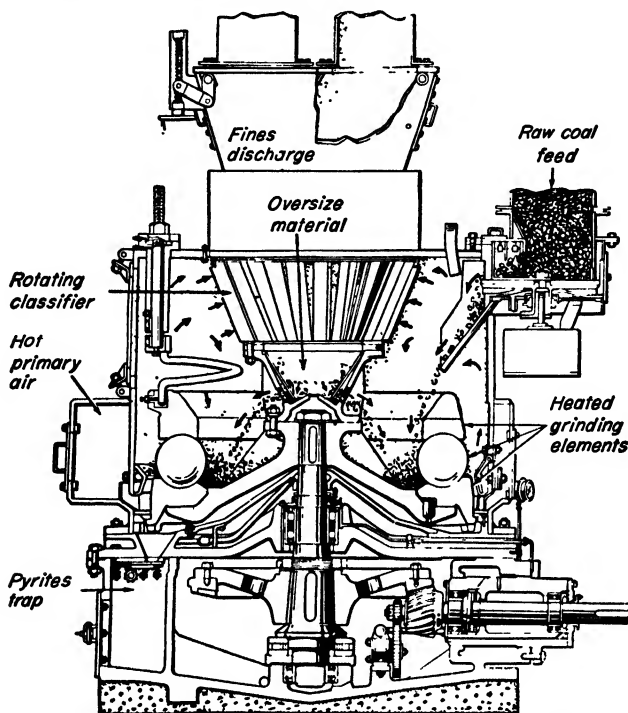


FIG. 17-13. Ball-race-type roller mill. Pulverization of the coal is accomplished by the ball-shaped grinding elements. Separation and drying of the fines is effected within the pulverizer by preheated primary air. (*The Babcock & Wilcox Co.*)

This type of mill is made in 17 sizes, ranging in capacity from 3,000 to 33,000 lb coal per hr, based on ABMA standard conditions. The ball-metal loss in weight per ton of coal ground varies directly with the abrasiveness of the coal being pulverized.

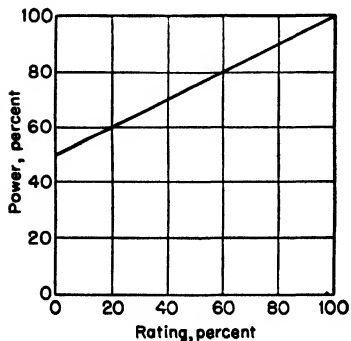


FIG. 17-14. Power characteristic curve for type E pulverizer. (*The Babcock & Wilcox Co.*)

**Bowl Mill.** A paddle type of feeder deposits the required amounts of coal into a revolving bowl (rim speed approximately 1,200 fpm) that carries the grinding ring. The rolls are stationary, do not contact the ring, and are positioned by adjustable springs. Centrifugal force moves the coal up the grinding face and over the rim. The slope of the grinding face retards the coal sufficiently so that it is nipped and crushed by the rolls and is thrown into the annular passage around the rim. Deflectors throw the larger particles, because of their inertia, back into the grinding zone. Pyrites

and tramp iron, because of their weight, are not lifted by the air velocity and drop to the mill bottom where they are swept into the tramp-iron spout (Fig. 17-15).

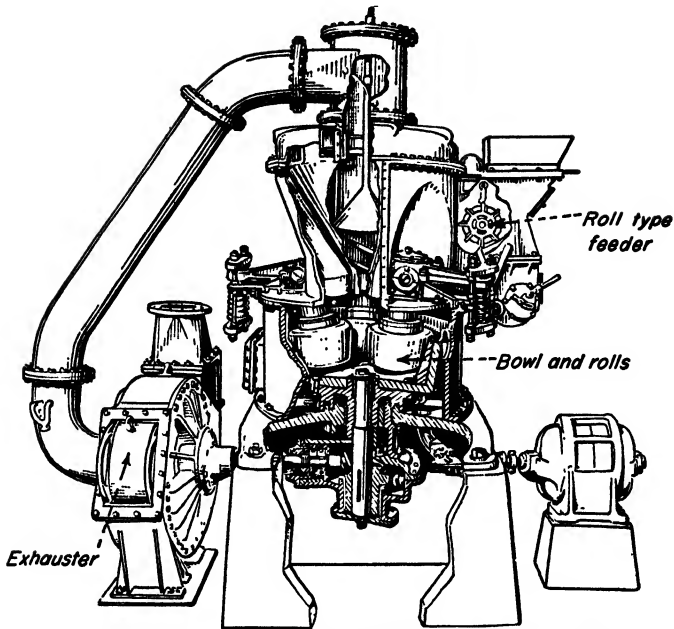


FIG. 17-15. Bowl-type roller mill. ("Combustion Engineering," 1st ed., p. 7-24.)

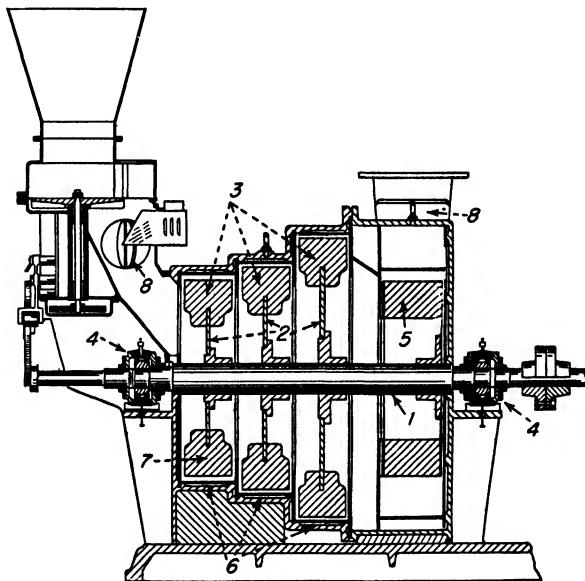


FIG. 17-16. Unitype—impact-type pulverizer. (1) Shaft; (2) hammer disks; (3) pulverizer hammers; (4) self-aligning bearings, dust-tight; (5) exhaustor fan; (6) renewable pulverizer chamber lining; (7) pocket for tramp material; (8) dampers for regulating primary air flow. (Erie City Iron Works.)

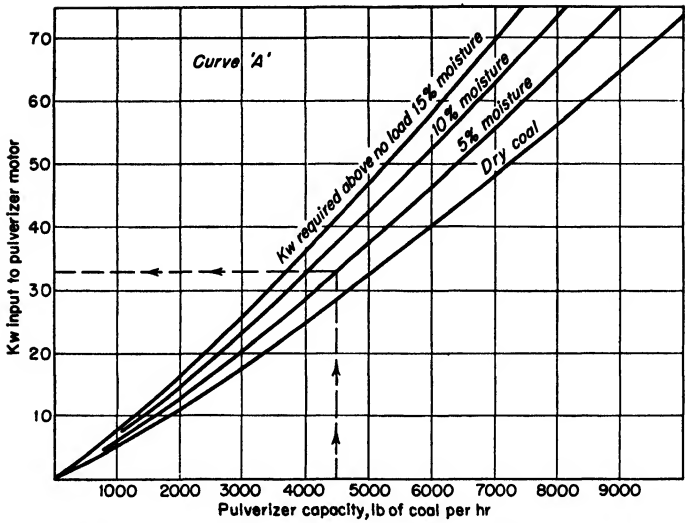


FIG. 17-17. Kilowatt input to pulverizer motor with varying moisture in coal based on 60 per cent grindability coal and 65 per cent through 200-mesh screen and 98 per cent through 50-mesh screen.

Size pulverizer	Max capacity, lb	No-load power, kw
A	1,500	4 5
B	2,500	6 5
C	4,500	10 0
D	7,500	14 5
E	10,000	18 0

(Erie City Iron Works.)

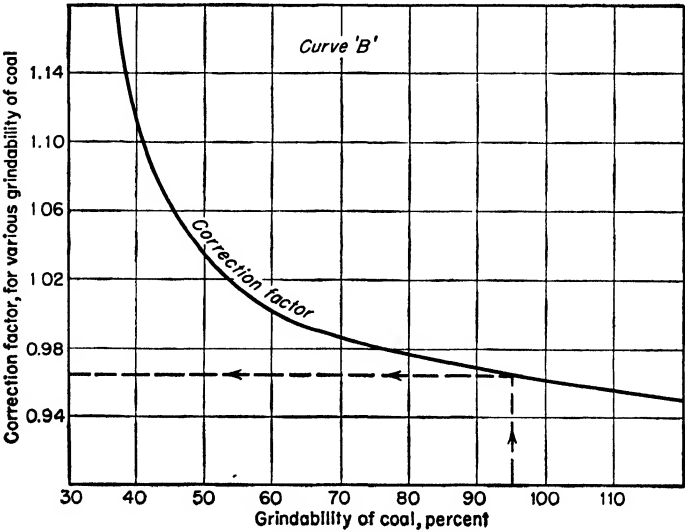


FIG. 17-18. Correction factor for varying grindability of coal based on 65 per cent through 200 mesh. To be multiplied to kw above no load only. (Erie City Iron Works.)

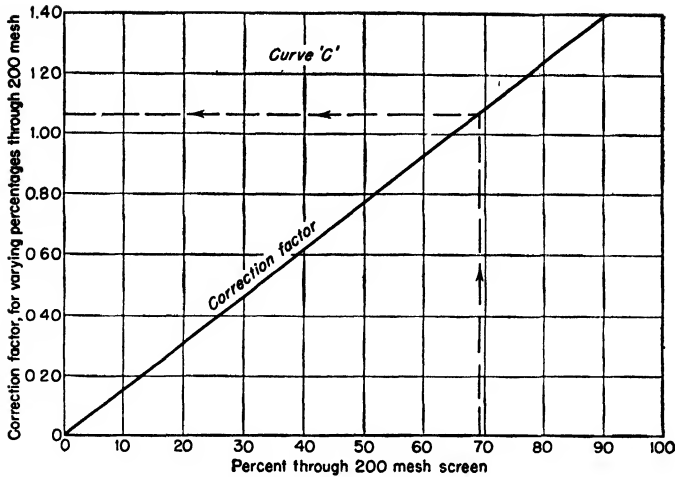


FIG. 17-19. Correction factors for varying percentages through 200 mesh. To be multiplied to kilowatts above no load. (*Erie City Iron Works.*)

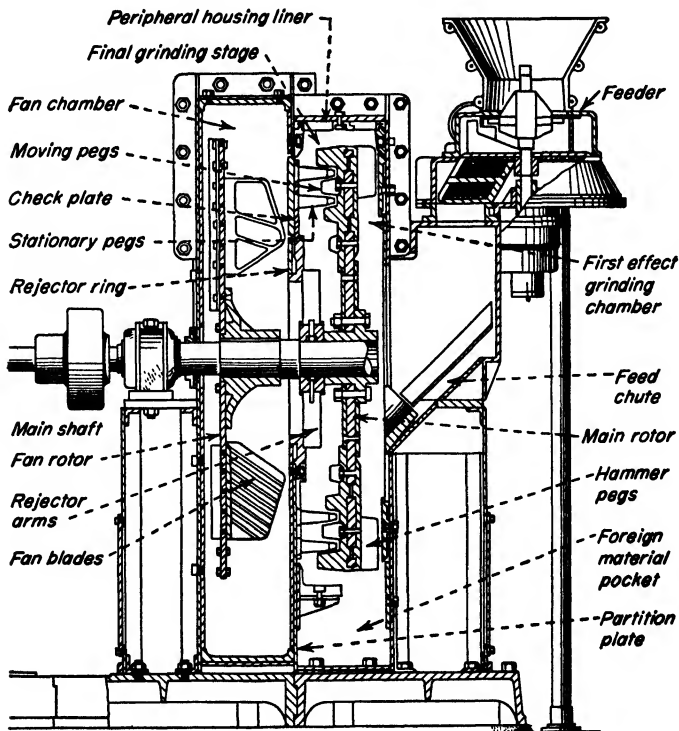


FIG. 17-20. Impact-type pulverizer—atrta. The raw coal is broken to a granular state by the hammer pegs, and then passes to the attrition stage where it is finally reduced. The fan draws the finely divided coal from the pulverizer section. Rejector arms throw back the larger particles for further reduction. (*Riley Stoker Corp.*)

The air stream sweeps the particles into a classifier which rejects the oversize which drops back into the mill. Hot air dries the coarse rejects as they drop, and they mix with the wet feed which helps to provide a lower moisture content in the grinding zone. An exhaust fan removes the fine coal from the classifier and discharges it to the burners.

Response to changes of load are effected by simultaneous control of raw-coal feed and air supply, which can be accomplished by some automatic system.

**Impact Mill—Unitype.** The feeder is of the table variety. After leaving the feeder, it passes over the face of a built-in electromagnet to remove the ferrous mate-

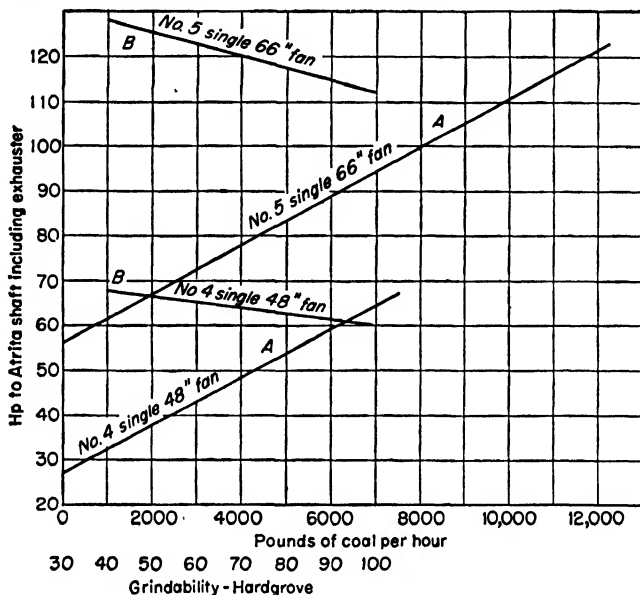


FIG. 17-21. Riley atrita performance. Curve A, power capacity 50 grindability 3 per cent moisture; Curve B, power at maximum capacity with various grindabilities and 3 per cent free moisture. For duplex atritas multiply power and capacity by two. (Riley Stoker Corp.)

rial. From here it passes on down to the first pulverizing pocket where other foreign materials are thrown into the tramp pocket. Pulverization is accomplished progressively in the three successive chambers indicated in Fig. 17-16, by hammers with chilled wearing surfaces. The pulverizing chambers are separated by steel diaphragms. The dimensions of the diaphragm openings are such that only coal of correct size is allowed to progress through the pulverizer. Removal of proper size coal is accomplished by means of a suitable air velocity through the mill. Air-regulating dampers are provided for selecting the correct air velocity to produce the desired pulverization while the mill is in action.

The performance of the Unitype pulverizer can be calculated from the curves of Figs. 17-17 to 17-19, *e.g.*, the power consumption of a 4,500-lb pulverizer at 5 per cent moisture, 95 per cent grindability, and 69 per cent through a 200-mesh screen. The total input to the motor will be

$$Kw = \text{no load} + (A \times B \times C)$$

No load from table, curve A = 10 kw

A from curve at 5 per cent moisture = 32.8 kw

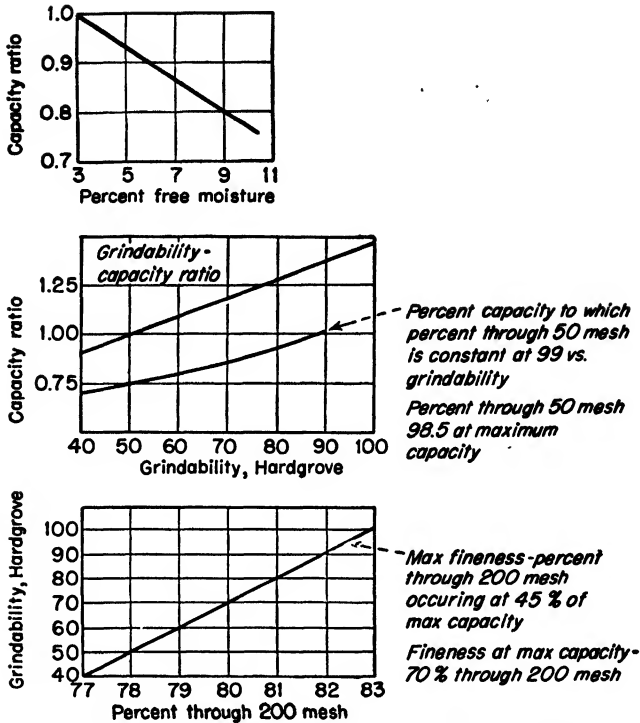


FIG. 17-22. Riley atrita performance. (Riley Stoker Corp.)

$B$  from curve at 95 per cent grindability = 0.964

$C$  from curve at 69 per cent fineness = 1.06

Inserting these values in the equation,

$$Kw = 10 + (32.8 \times 0.964 \times 1.06) = 43.6\text{-kw input}$$

To change this figure to kilowatt-hours per ton, it is necessary only to multiply by 2,000 lb per ton and divide by the rate per hour:

$$\text{Kwhr at 4,500 lb/hr} = 43.6 \times \frac{2,000}{4,500} = 19.3$$

**Impact Mill—Atrita.** The feeder is the roll type, depositing the coal on a short belt. One of the pulleys is of the magnetic type that deposits the ferrous foreign material in a pocket. The coal then drops to the first, or impact, stage of the mill, where the raw coal is broken down to a granular state. From the first stage, the coal passes to the attrition stage, with the coal in suspension in a high state of turbulence. After the coal is reduced in size, the suction fan draws the coal from the pul-

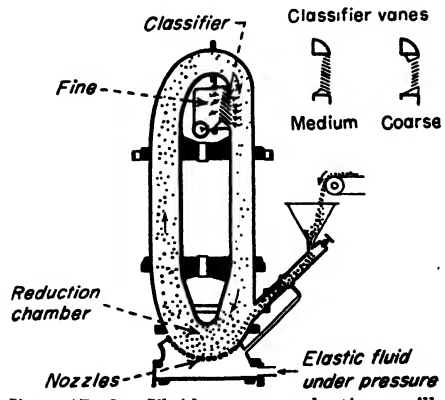


FIG. 17-23. Fluid-energy reduction mill. Jet action in the reduction chamber breaks up the individual particles by impact and abrasion against each other. (C. H. Wheeler Mfg. Co.)

verizer section. Scoop-shaped rejector arms reject the heavier particles centrifugally and send them back for further reduction, while the finer particles are discharged to the burners. Refer to Figs. 17-20 to 17-22.

**Attrition Mills.** The fluid-energy reduction mill effects the reduction of particle size by impact and attrition, as indicated in Fig. 17-23. Feed material entering the reduction chamber is entrained by the stream of circulating fluid, which may be either a gas or a vapor, or a combination of the two. Common fluids are compressed air and superheated steam. The jet action in the reduction chamber causes the material being reduced to break by impact and abrasion of particles against each other. Particles are carried up and around to the classifier where centrifugal force shifts the larger particles toward the outer periphery. Part of the circulating fluid changes direction and flows out through the classifier vanes, carrying with it the particles small enough to be diverted by the viscous drag of the outgoing fluid. Because of their greater inertia, the larger particles are carried on down to the reduction chamber for further reduction.

This type of mill has been applied to the pulverization of coals and other solid fuels. The mixtures of fluid and fuel in suspension have been transported to combustion chambers and burned successfully. Performances claimed are shown in Table 17-17.

**Table 17-17. Performances, Attrition-type Mill<sup>1</sup>**  
(Elastic fluid type. Feed material, Koppers Federal No. 1 bituminous coal)

	Steam	Air
Size . . . . .	4 mesh-0	4 mesh-0
Feed rate, lb/hr	2,100-3,360	1,200 1,880
Steam consumption, lb/ton	2,500-1,328	
Power consumption, hp/ton		285-225
Particle-size analysis:		
On 48 mesh, cumulative per cent	0-2 12	0-3 4
On 200 mesh, cumulative per cent	0.24-10 00	0-7 4
On 325 mesh, cumulative per cent	1 00-16 60	0 50-15 0

NOTE: Mill performances on lignites are somewhat better than those shown above.

<sup>1</sup> C. H. Wheeler Mfg. Co.

## PULVERIZED-COAL DISTRIBUTION

**Distribution Methods.<sup>1</sup>** There are four systems generally used in the distributing of pulverized coal, *viz.*:

1. Bin system
2. Direct-firing system
3. Central pulverized-coal circulating system
4. Direct-fired circulating system

The advantages<sup>2</sup> and disadvantages of the bin system relative to the direct-fired or unit system have been discussed in the literature a number of times. Some of the outstanding features listed are as follows.

### Advantages of the Bin System.

1. The coal may be pulverized at a constant rate independent of load and during off-peak hours.
2. A breakdown of the pulverizing mill will not necessitate a shutdown, since ample storage space is available.

<sup>1</sup> SHEERMAN, D. V., Development and Application of Coal-pulverizing and Burning Equipment for Industrial Furnaces and Steam Generation, *Bull.* 3-392, pp. 11-17, Babcock & Wilcox Co., New York, 1946. (Adapted from report to the Federal Power Commission Natural Gas Investigation, Docket No. G-580.)

<sup>2</sup> GAFFERT, GUSTAV A., "Steam Power Stations," 3d ed., p. 317, McGraw-Hill Book Company Inc., New York, 1946.

3. The mills can be set to pulverize at the most economical rate and at a constant degree of fineness.

4. Wear on the mill does not affect fineness of coal or the capacity of the boiler.

5. The boiler room may be kept clean.

**Advantages of the Direct-fired System.**

1. It is lower in cost for pulverizer equipment, since storage space or additional building is not required.

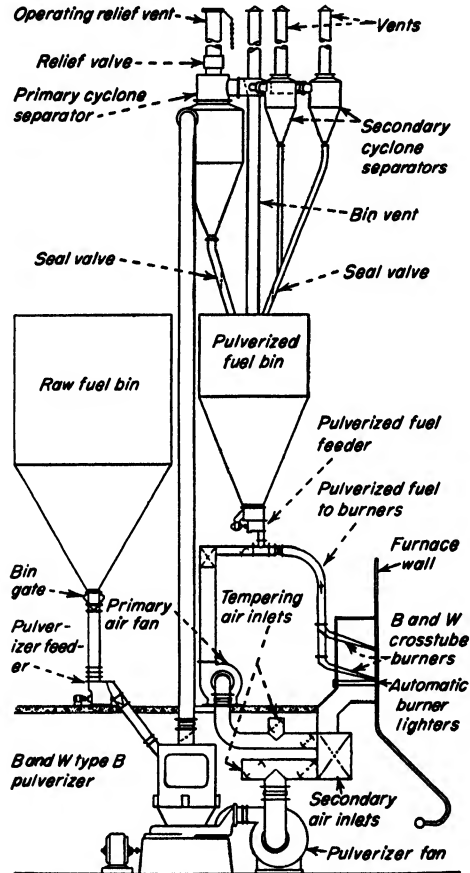


FIG. 17-24. Bin system. (The Babcock & Wilcox Co.)

2. No fire hazard is present owing to absence of pulverized-fuel storage in the boiler room.

3. It is not necessary to dry the coal before it is fed to the mill.

4. Even with greater variation in degree of fineness, the efficiency obtainable with the unit system and the same boiler is within the limits of test accuracy of the efficiency obtainable with the bin or storage system.

**Bin System.** Figure 17-24 illustrates this type of system. Raw coal flows by gravity into an automatically controlled feeder which feeds coal to the pulverizer at the maximum rate the pulverizer is capable of grinding at specified fineness. Here the coal is dried, pulverized, and classified. The finished product is pneumatically



conveyed into cyclone collectors where approximately 98 per cent of the coal is separated. The exhaust from the cyclones passes through bag filters or gas washers, and the air together with moisture vapor is vented to the atmosphere. The finished product from the cyclones and filter is discharged by gravity into a storage bin. From here, the coal is conveyed by pneumatic transport system through pipe lines to bins at points where it is used. A typical transport system is shown by Fig. 17-25. Pulverized coal from the bins is fed to the burners by special feeders and aerating devices, the rate of feed being controlled by the speed of the feeder. Generally speaking, the bin system is no longer being considered for new installations in the metallurgical industry or for steam generation, because the direct-firing system offers greater advantages in simplicity, cost of operation, and lower investment.

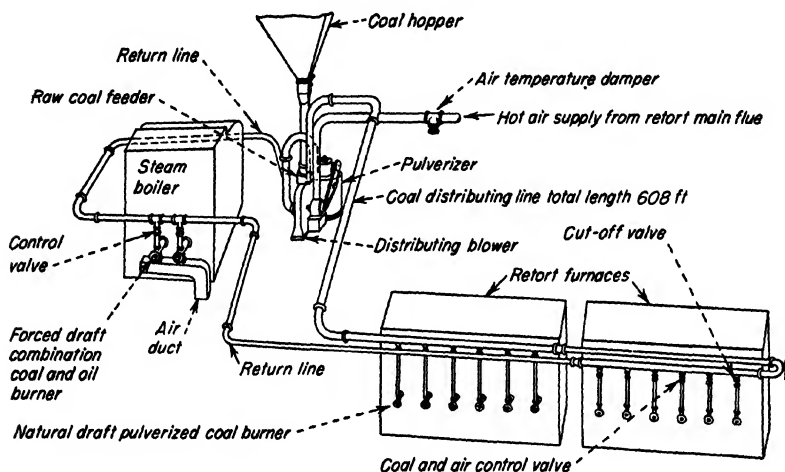


FIG. 17-25. Direct-fired circulating system. Firing chemical retort furnaces and steam boilers as installed in 1944 at Stauffer Chemical Co., Bentonville, Va. Capacity 23,000,000 Btu per hour. Length of line 608 ft. (*The Babcock & Wilcox Bull.* No. 3-392.)

**Direct-fired System.** The raw coal is metered through a raw-coal feeder, as shown in Fig. 17-26, to the pulverizer. Here the coal is dried by preheated air, pulverized, and classified. The fine coal is sent directly through pipes to the burners, with no intermediate storage of pulverized coal.

Direct-firing installations are simple and efficient in operation, and the system is well adapted to automatic control. Within the last fifteen years practically all the pulverized-coal installations for steam generation have been of the direct-firing type; and, with the exception of a few cases in recent years, this also applies to the metallurgical and cement industry.

**Central Pulverized-coal Circulating System.** A typical arrangement of this type is shown in Fig. 17-27. This system is comprised of a central preparation plant, from which the pulverized coal is distributed through a circulating line. The coal is supplied to various furnaces through take-offs and the rate controlled by valves. The surplus coal is returned to the central plant, where it is separated, the coal being discharged into the storage bin, and the air is induced to the system by the distributing fan, completing the cycle.

This system was used extensively during the early application of pulverized-coal firing of metallurgical furnaces; but because of its inherent complications, it has been in many cases replaced by simpler systems, such as direct firing.

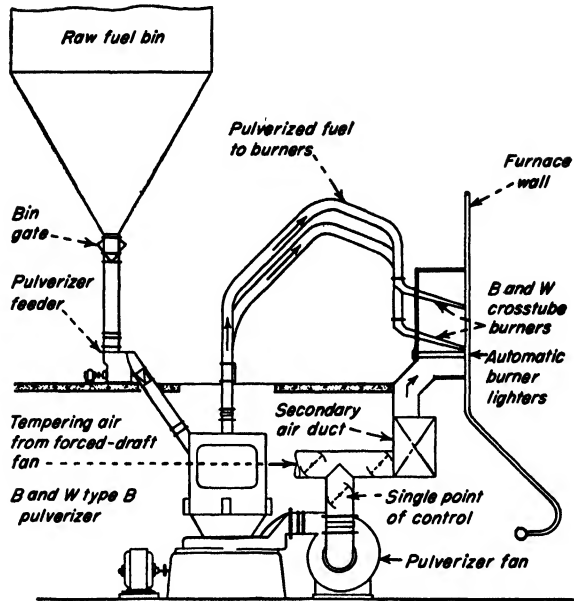


FIG. 17-26. Direct firing system. (The Babcock & Wilcox Co.)

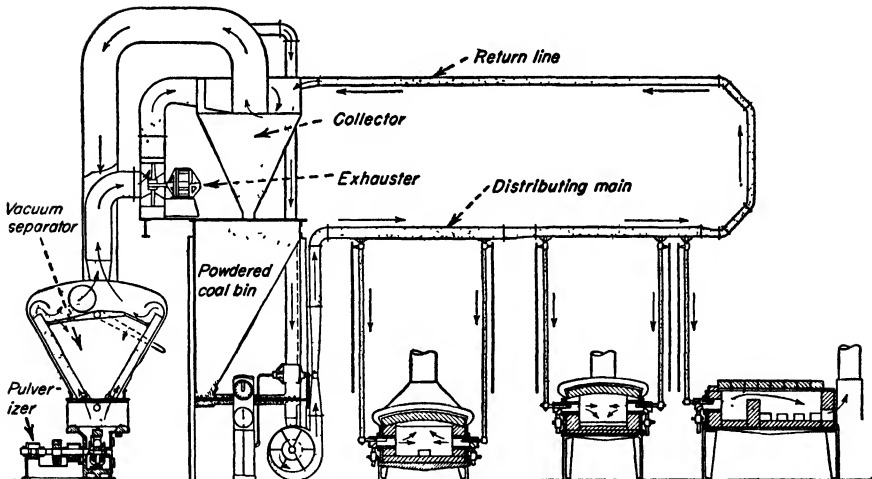


FIG. 17-27. Central pulverized-coal circulating system. (Babcock & Wilcox Bull. No. 3-392.)

**Direct-fired Circulating System.** Figure 17-25 shows a typical installation of this type. This system consists of a preheated air supply, pulverizer, automatically controlled coal feeder, pulverizer fan, distributing lines, and control valves. Briefly, it is a modification of the direct-firing system in that it serves a plurality of furnaces that may be located in separate areas throughout a plant, with the coal supply to each independently controlled.



## SECTION 6

### **FUEL-HANDLING METHODS**



## CHAPTER 18

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### HANDLING AND STORING SOLID FUELS

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## COAL-HANDLING EQUIPMENT

**Solid-fuel handling**, of which coal handling occupies the position of major importance, involves the transportation of the coal (whether delivered by truck, water, or rail) from the delivery point to storage, reclamation from storage, and thence to the combustion equipment. Because plant size largely governs the type of equipment used, the following data are grouped according to small, medium, and large plants. With such arbitrary groupings, there is some overlapping between these groups of equipment utilized. In general, it is advisable to handle the plant coal requirements in a maximum time of one shift of 8 hr, but it is more desirable to allow time for a possible breakdown repair to handle the coal in 4 to 6 hr. The shorter period also allows the personnel more time for operational duties. The final selection of the equipment should depend not only on the suitability of the machinery, but also on an economic study of the fixed and the operating costs to determine which of the alternate systems has the lowest total annual cost. In addition, ash handling is of major importance, and in some plants the coal and ash systems are closely integrated.

**Coal- and Ash-handling Construction Material.**<sup>1</sup> Beside corrosion, wear is the most important force in making metal articles unserviceable. For wear to occur, there must be penetration of the surface or displacement of particles at the surface; and, secondly, the displaced particles must be detached. Resistance to penetration or displacement of particles at a metal surface should increase with metal hardness; but, of two steels of equal hardness, the tougher one sometimes may resist wear better because it should be more difficult to detach misplaced tough particles than brittle ones. Hence, strength and toughness can both contribute to wearing properties.

When the exposures involve pounding or heavy pressure, as in rock-crushing parts, the outstanding steel to defeat wear is Hadfield's steel. This 12 % manganese steel over pearlitic steels is illustrated by Hall, who gives results obtained in a small stone crusher using jaw plates 6 by 6 by 1 in. in reducing at least 20,000 lb of 34-in. blue traprock to dust as follows: 12 % manganese steel, rate of wear 1.00; 0.20 to 0.30 % carbon, 1.20; 1.40 % manganese steel, rate of wear 7.26.

In coal-tipple and conveyor chutes handling some 1,800 tons per hr, mild steel handled 1.1 million tons of coal, austenitic 14 % manganese steel 1.5 million tons,

**Table 18-1. Life of Mild and Two-alloy Steels in Skip Liner<sup>1</sup>**  
(Plates, Creighton Mine No. 3 shaft)

Material	Approx Brinell hardness	Plate thickness, in.	Tons ore hoisted	Weight loss, lb/sq ft/ 10,000 tons ore	Relative rates of wear
Lower front side liners					
Mild steel . . . . .	170	$\frac{1}{2}$	216,254	0 304	1 00
SAE 2320 . . . . .	200	$\frac{3}{4}$	163,830	0 205	0 67
(0.20 % C, 3.5 % Ni) SAE 3160 type . . . . .	300	$\frac{1}{2}$	333,911	0 160	0 53
Lower middle side liners					
Mild steel . . . . .	170	$\frac{1}{2}$	216,254	0 422	1 00
SAE 2320 . . . . .	200	$\frac{3}{4}$	163,830	0 283	0 67
SAE 3160 type . . . . .	300	$\frac{1}{2}$	333,911	0 204	0 48

<sup>1</sup> FRENCH, HERBERT J., *Progress in Alloy Steels, Mining Met.*, pp. 336-339, June, 1948.

and the medium-manganese steel about 2.4 million tons. In ash hoppers in a power plant, cast-iron plates had a life of about 1 month, whereas  $\frac{1}{2}$ -in. test plates of the 1.75 % manganese steel were still in usable condition after 8 months.

When nonmetallic materials being handled are wet, corrosion may become a significant factor in the wear rates and ultimate life. As shown in Table 18-1, when mild-steel liner plates were replaced with low-carbon 3.5 % nickel steel, a reduction of about one-third in the rate of deterioration was secured. Raising the carbon content and adding chromium along with the small amounts of nickel resulted in a further decrease in the rate of deterioration to about half that of mild steel.

### Small Plants

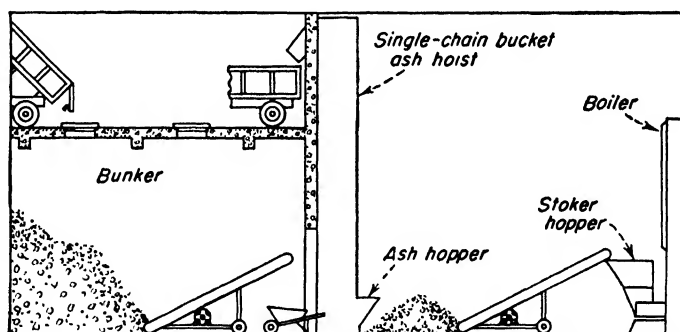
**Small plants**, burning as low as a few tons per day, can economically utilize some form of mechanical handling. It must be remembered, where hard sustained work is involved, that a man is capable of only an average of  $\frac{1}{10}$  hp for an 8-hr day. Advantages of mechanical handling are:

1. Improvement of working conditions by the elimination of hard labor and the attendant dirt

2. Release of the personnel to operational duties

3. Lower mechanical handling costs than manual handling costs

**Truck Service.** In some smaller plants, where manual handling predominates, coal is dumped from the truck into basement bunkers. Hand wheelbarrows, manually



Farguhar portable conveyor - No. 331-10' cleated belt type - capacity 1 ton/min. - weight 375 lb. - H.P.=1 - belt length-10 ft. - height of discharge 4'-6".

FIG. 18-1. Small portable conveyor application.

loaded, distribute the coal to the boilers. There it is either hand-fired on grates or shoveled into hoppers feeding the stokers. Ashes are removed by a hand-operated hoist that lifts the filled ash cans to the street level. For truck service, see also Fig. 18-34.

As the plant size increases, labor savings can be effected by the use of portable conveyors, as shown in Fig. 18-1. Wheelbarrows are loaded at the pile by the conveyor. These are dumped on the conveyor at the stoker. The conveyor, weighing only 375 lb, can readily be moved from stoker to stoker. In the background is a single-chain bucket ash hoist. As the ashes are scraped from the ashpit, they are loaded into a wheelbarrow, which is dumped alongside the ash hoist. When the ashes have accumulated sufficiently, the portable conveyor is used to load the ash hoist, which discharges into the truck. While this system is laborsaving, there is still a good deal of dirt in the air and manual labor involved.



**Railroad Service.** Where the small plant is serviced by railroads, a portable conveyor is useful for both stock pile and reclamation. Figure 18-2 shows such a con-

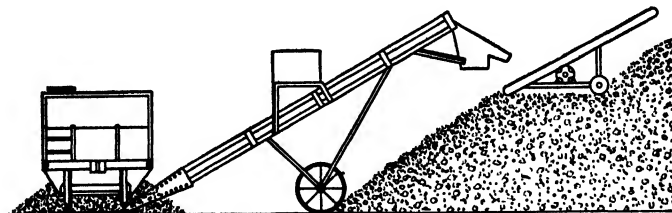


FIG. 18-2. Model 334-3, cleated-belt type. Capacity: 14-in. belt—90 tons/hr; 18-in. belt—120 tons/hr. Standard sizes (width  $\times$  length): 14 in.  $\times$  20 ft, 14 in.  $\times$  25 ft, 18 in.  $\times$  30 ft, 18 in.  $\times$  35 ft, 18 in.  $\times$  40 ft.

veyor unloading a hopper bottom car (Farquhar Co., York, Pa.; Barber-Greene, Aurora, Ill.; and Jeffrey Mfg. Co., Columbus, Ohio). The coal drops on the feed end of the conveyor, travels up the conveyor, screened if desired, and is deposited on the stock pile. Flow is unsteady, and the conveyor is alternately overloaded and part loaded. A ton or more of coal remains on the track to be hand-shoveled. The conveyor averages  $1\frac{1}{2}$  hr for a 50-ton car. The small conveyor shown in Fig. 18-2 can

be used to increase the stock pile. There are variations of this basic type. Manufacturers differ as to size and capacity. Plain belts, cleated belts, or trough types are offered to handle various coal sizings. Other units are self-propelled. Where clean

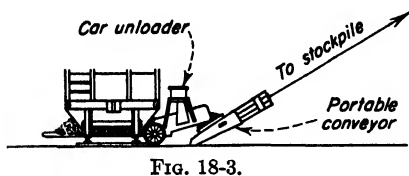


FIG. 18-3.

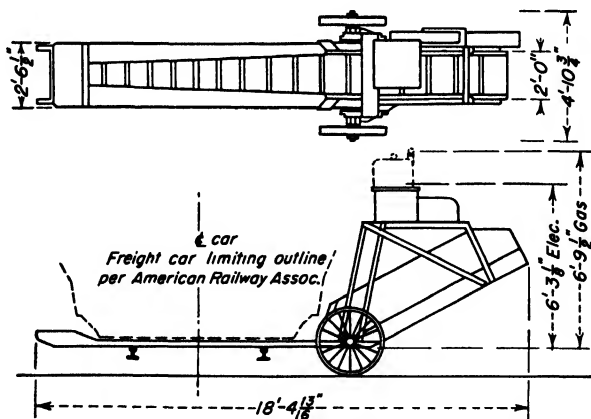


FIG. 18-4. Capacity of a car unloader rated at two capacities depending on the flight-line speed used. Low capacity is  $\frac{3}{4}$  to  $1\frac{1}{2}$  tons of coal/min; high capacity is 1 to 2 tons/min. Weight of power-propelled unit with gas drive is 3,840 lb; weight of same but with electric motor, 3,280 lb. Horsepower, 7.9 (gasoline engine) and 3 or 5 (electric motor). Minimum discharge height, 3 ft to center line of head shaft.

coal is required, screens are placed on the discharge. These screens are either stationary or the shaker type.

Figures 18-3 and 18-4 illustrate an improvement that eliminates the alternate overload and part load and clean-up disadvantages of Fig. 18-2. The car unloader (A. B.

Farquhar Co., York, Pa.; Barber-Greene Co., Aurora, Ill.) feeds the coal evenly to the conveyor and practically eliminates clean-up. At an average rate of 1 to 2 tons per min, a 50-ton car can be unloaded in 30 min to 1 hr.

An additional advantage is the elimination of the fixed pit or track hopper under the track shown in Fig. 18-8. The car unloader also provides greater flexibility of location of the stock pile, since some models are not only portable but also self-propelled.

**Weigh Larries.** Fundamentally a weigh larry is a plate-steel hopper suspended on scale irons, the whole being mounted on a truck which runs on tracks immediately

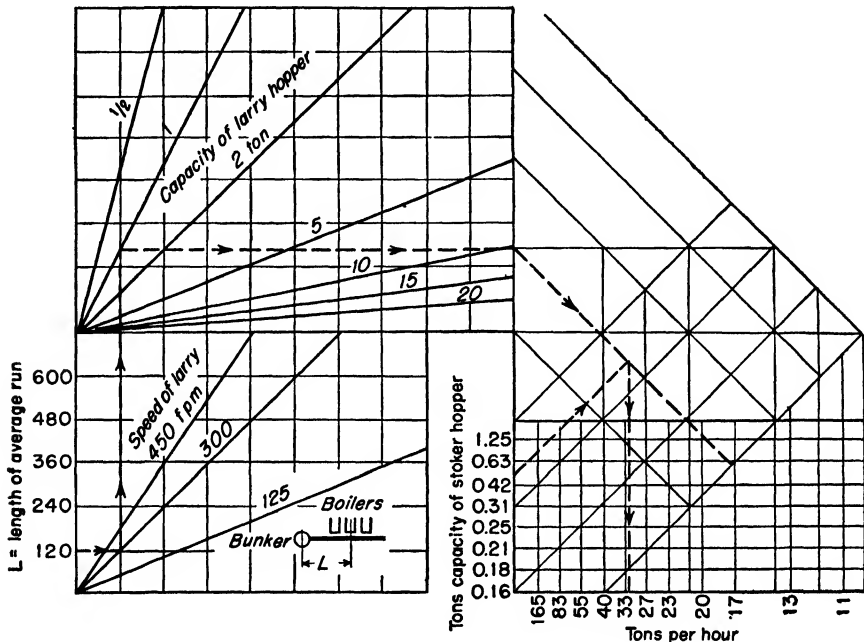


FIG. 18-5. Beaumont-Birch weigh larry capacity chart. To determine the capacity in tons per hour for a larry under a given condition, enter chart at "Length of average run," go horizontally to speed of larry desired, then vertically to capacity of larry, then horizontally to outer right vertical line, then downward at 45°. Enter again at capacity of stoker hopper, run upward at 45° to intersection of other 45° line, then downward vertically to tons per hour. Example:  $L = 120$  ft. Speed = 300 ft per min. Capacity = 1 ton. Stoker hopper = 0.5 ton. Tons per hour = 32. NOTE: This chart is for 12- by 16-in. bunker gates and 12 by 18-in. larry discharge chutes.

beneath the coal bunker and for the full length of the boiler room. The coal is drawn into the larry from the bunkers and then discharged to the stokers as needed. The capacity chart (Fig. 18-5) shows sizes ranging from  $\frac{1}{2}$  to 20 tons, a wide enough range to fulfill requirements from the small industrial plant to the central station.

To determine the capacity in tons per hour for a larry under given conditions, enter chart at "Length of Average Run," go horizontally to speed of larry desired, then vertically to capacity of larry, then horizontally to outer vertical line, then downward at 45 deg. Enter again at capacity of stoker hopper, run upward at 45 deg to intersection of other 45-deg line, then vertically downward to tons per hour.

The weigh larry has a number of advantages that lend its use to multiple boiler firing, where the firing aisle is long. For instance, the long suspension bunker with

Table 18-2. Small-plant Equipment

Coal consumed, tons/24 hr	Type of delivery	Handling system	Advantages	Disadvantages
0-5	Truck	Coal, wheelbarrow. Ash, hand hoist	Low first cost	High labor cost. Dirt in atmosphere
5-10	Truck	Coal, small portable conveyor. Ash, single-chain bucket hoist	Reduced labor cost. Higher capacity	Dirt in atmosphere. Increased first cost. Equipment maintenance and breakdown possibility
10-20	Railroad	Coal, conveyor to and from stock pile. Chutes in plant. Car, unloader plus conveyor	Reduced labor cost. Higher capacity	Dirt in atmosphere. Increased first cost. Equipment maintenance and breakdown possibility
10-20	Truck	Coal, hopper to bucket elevator to silo. Ash, small car or hoist	Reduced labor cost. Higher capacity. Dry coal storage, less dirt in atmosphere	Increased first cost. Equipment maintenance and breakdown possibility

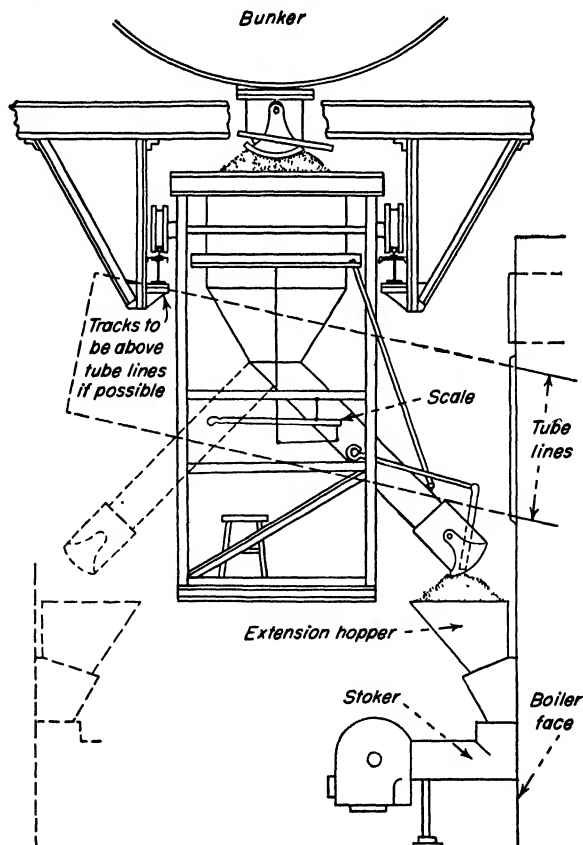


FIG. 18-6. Beaumont-Birch coal weigh larry, two-ton capacity, motor driven.

its distributing machinery is unnecessary, and in its place a single bunker to load the larry is used. With this construction the discharge gates can be spaced at closer centers, eliminating the arching and dead coal troubles of the wider spaced gates of the suspension bunker. An accurate record is kept of all the coal consumed by each boiler, by means of a ticket recorder on the scale beam. Thus the efficiency of each boiler may be readily calculated. Stoker extension hoppers are added to the stoker magazines, and enough coal is added to the stoker in a few minutes to last for several hours. A larry distributes the coal over the full length of the stoker magazine, while, with spreader chutes, lumps separate from the fines and roll to the side of the stoker, which causes troublesome and inefficient firing in some stokers. Clogging of chutes is eliminated, as the operator is in a position to observe the discharge of each load.

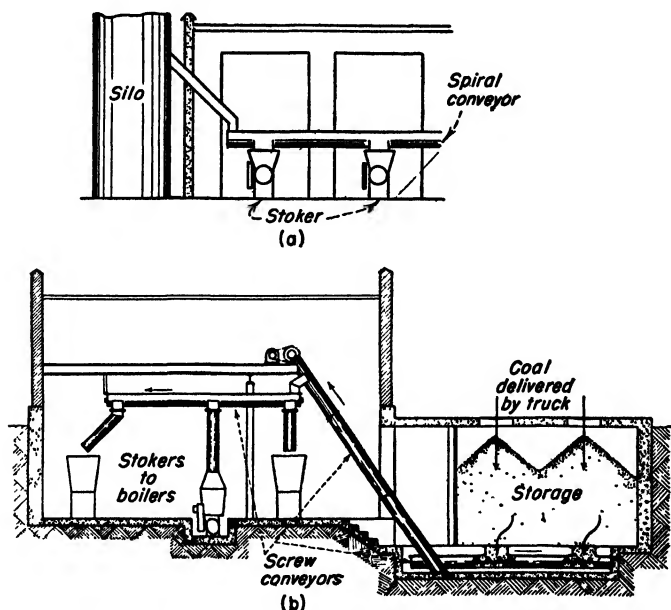


FIG. 18-7. Two-spiral conveyor applications to stoker feeding.

In case of fire in the bunker, the operator can readily carry the smoldering coal to all the stokers, an obvious impossibility with the suspension bunker and chutes (Fig. 18-6). For additional information on the weigh larry, consult the following manufacturers: Beaumont-Birch, Philadelphia, Pa.; Stephens-Adamson Mfg. Co., Aurora, Ill.; C. O. Bartlett & Snow Co., Cleveland, Ohio; Gifford-Wood Co., Hudson, N.Y.; and others.

**Spiral conveyors** having no return strand require a minimum of operating space and hence find application where space over bunkers is limited and where high capacities are not required. In smaller plants where bunker space is not available, the spiral conveyor can be used to carry the coal from a storage silo or from the elevator to the stoker hoppers, as shown in Fig. 18-7. By means of suitable slide gates or valves, the coal can be discharged at any point along the length of the conveyor.

**Maximum length** of a spiral conveyor is dependent upon the strength or torque value of its pipe or couplings. For convenience in determination of the maximum length, the torque value of the various sizes of conveyors has been reduced to terms of horsepower at 100 rpm and is so listed in Table 18-3 in the last column. As horse-

power is a function of speed, the horsepower values at speeds other than 100 rpm are readily determined by direct proportion. Thus, at a speed of 50 rpm, the horsepower value of the pipe will be one-half ( $\frac{1}{2}$ ) the value at 100 rpm; at 150 rpm, it will be one and one-half ( $1\frac{1}{2}$ ) times that at 100 rpm, and so forth.

**Horsepower** required to drive a spiral conveyor depends entirely on the nature of the material handled, and any general formula can be only approximately correct. However, the values obtained from the following formula, according to Jeffrey Mfg. Co., have been found to be very acceptable and may be depended upon for all ordinary work.

$$H_p = \frac{L(AN + 2TF)}{1,000}$$

where  $T$  = capacity of conveyor, tons/hr

$L$  = length of conveyor, ft

$F$  = material factor: 1.0 for coal, 2.0 for ashes

$A$  = hanger factor: 0.15 for babbitted hangers, 0.4 for hard-iron hangers

$N$  = speed of conveyor, rpm

In determining the size of the motor, allow extra power to take care of losses of the driving equipment. Where inclined conveyors are used, allow sufficient power of the lift. Values in Table 18-3 are for steel conveyor handling coal and dry ashes.

**Table 18-3. Sizes, Capacities, and Horsepowers of Spiral Conveyors<sup>1</sup>**

Diam Con- veyor, in.	Diam coup- ling shaft, in.	Size of pipe, in.	Coal					Ashes					Max hp of con- veyor at 100 rpm
			Max uni- form size	Max un- sized <sup>a</sup>	Max capac- ity, cu ft /hr <sup>b</sup>	Gauge flights	Max speed, rpm	Max uni- form size	Max un- sized <sup>a</sup>	Max capac- ity, cu ft /hr <sup>c</sup>	Gauge flights	Max speed, rpm	
4 <sup>d</sup>	1	1 $\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$	65	16	120						1 5
6	1 $\frac{1}{2}$	2	$\frac{1}{2}$	$\frac{3}{4}$	215	16	115	$\frac{3}{4}$	1 $\frac{1}{2}$	21	$\frac{3}{16}$	33	5 0
9	1 $\frac{1}{2}$	2	$\frac{3}{4}$	1 $\frac{1}{2}$	710	14	105	1 $\frac{1}{2}$	2 $\frac{1}{4}$	72	$\frac{3}{16}$	32	5 0
9	2	2 $\frac{1}{16}$	$\frac{3}{4}$	1 $\frac{1}{2}$	710	14	105	1 $\frac{1}{2}$	2 $\frac{1}{4}$	72	$\frac{1}{4}$	32	10 0
10	2	2	$\frac{3}{4}$	1 $\frac{1}{2}$	950	14	100	1 $\frac{1}{2}$	2 $\frac{1}{2}$	100	$\frac{1}{4}$	31	10 0
12	2	2 $\frac{1}{16}$	1	2	1,500	12	95	2	3	160	$\frac{1}{4}$	30	10 0
12	2 $\frac{1}{16}$	3	1	2	1,500	12	95	2	3	160	$\frac{1}{4}$	30	15 0
12	3	3 $\frac{1}{2}$	1	2	1,500	$\frac{3}{16}$	95	2	3	160	$\frac{1}{4}$	30	25 0
14	2 $\frac{1}{16}$	3	1 $\frac{1}{4}$	2 $\frac{1}{2}$	2,350	$\frac{3}{16}$	90						15 0
14	3	3 $\frac{1}{2}$	1 $\frac{1}{4}$	2 $\frac{1}{2}$	2,350	$\frac{3}{16}$	90	2 $\frac{1}{2}$	3 $\frac{1}{2}$	240	$\frac{1}{4}$	28	25 0
16	3	3 $\frac{1}{2}$	1 $\frac{1}{2}$	3	3,200	$\frac{3}{16}$	85	3	4	340	$\frac{1}{4}$	27	25 0
18 <sup>e</sup>	3	3 $\frac{1}{2}$	2	3	4,550	$\frac{1}{4}$	80	3	4 $\frac{1}{2}$	490	$\frac{3}{8}$	26	25 0
20 <sup>e</sup>	3	4	2	3 $\frac{1}{2}$	5,900	$\frac{1}{4}$	75	3 $\frac{1}{2}$	5	650	$\frac{3}{8}$	25	25 0
20 <sup>e</sup>	3 $\frac{1}{16}$	4	2	3 $\frac{1}{2}$	5,900	$\frac{3}{8}$	75	3 $\frac{1}{2}$	5	650	$\frac{3}{8}$	25	40 0

<sup>1</sup> The Jeffrey Mfg. Co.

<sup>a</sup> Not more than 25 per cent of total.

<sup>b</sup> 38 per cent full. } Capacities given are at maximum rpm uniform and continuous flow of material

<sup>c</sup> 12 $\frac{1}{2}$  per cent full. } for 1 hr.

<sup>d</sup> Helicoid conveyor only.

<sup>e</sup> Sectional conveyor only.

Jeffrey recommends cast-iron conveyor. The values given above are given not as specific rules but as guides in good general practice wherein there are acceptable variations depending upon the nature of the material handled, nature of the service, power consumption, and the life of the conveyor. Conveyors handling coal are furnished with babbitted bearing hangers, and for ashes with hard iron bearing hangers, unless otherwise specified.

### Medium Plants

**Track Hoppers, Grates.** Grates are usually set over track hoppers to eliminate oversize or foreign material such as car stakes or mine props. Openings are set to pass maximum size desired.

Track hoppers are usually made of steel plate with suitable stiffeners. Rail supports are I beams designed for the particular loads expected. Where feeders are used, they are fastened to the bottom of the hoppers. When the hoppers are housed, care must be taken to ensure ample working clearance for the personnel. In some cases the hopper house is fitted with doors and the whole house heated to thaw out frozen coal (Fig. 18-8).

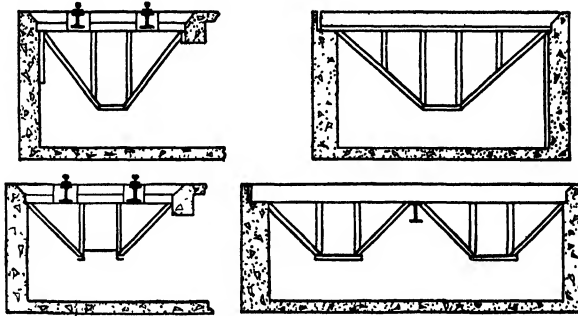


FIG. 18-8. Long and square car hoppers.

**Feeders.** Some form of feeder is usually attached to the bottom of the hopper. The feeder is necessary to ensure an even flow of coal to the crusher. The crusher then operates at maximum efficiency without over- or underload. Reciprocating plate feeders consist of a roller-supported plate oscillated by an eccentric drive (Fig. 18-9). On the forward stroke, material is carried from the hopper. On the return stroke, the plate slides back under the material, which then falls down through opening *E*. This feeder is simple in construction and operation. Rate of flow is changed by varying the speed, the throw, or the size of the opening from the hopper. Very little headroom is required.

Another common feeder is the apron shown in Fig. 18-10. These are made of overlapping steel pans mounted on roller chains for light and heavy duty. When the feeder is inclined upward, depth of excavation is saved. This type has a disadvantage in that the pit has to be cleaned periodically because wet coal particles cling to the plates and drop off on the return.

**Coal crushers** are made in a number of types by Stephens-Adamson, Link-Belt, Bartlett-Snow, Pennsylvania Crusher Co., and others. In general, these types consist of the crushing roll, the swinging hammer, and the revolving drum or Bradford breaker. For further descriptive material, see Coal Crushers. To ensure smoother crusher operation and uniform sizing, some form of feeder should be used. The reciprocating feeder, the simplest variety, gives a pulsating flow which two such feeders, operating alternately, tend to smooth out. The apron feeder gives a much smoother feed. If the crusher is placed under the feed hopper with no feeder, there is always the danger of choking the crusher or flooding the conveyor under the crusher.

**Coal-distributing Machinery.** The coal, after being crushed, must be elevated and distributed to storage or to the stokers. Plant arrangement and capacity dictate the type of equipment to be used.

**Skip hoists** are manufactured by Bartlett & Snow, Stephens-Adamson, Beaumont-Birch, and others. Essentially this type of equipment consists of a single bucket or

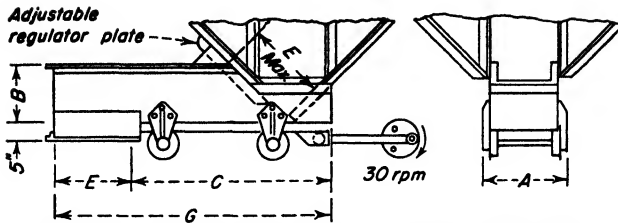


FIG. 18-9. Stephens-Adamson reciprocating plate feeder.

Width outside, A, in.	Length of reciprocating plate, C, ft and in.	Depth of skirt plate, B, in.	Capacity, tons per hour	Maximum opening, E, in.	Length of skirt plate, G, ft and in.	Horsepower required
14 1/2	4—8	12	23	17	5—9	1/2 to 1
14 3/4	5—3	18	34	25	7—0	3/2 to 1 1/2
16 1/2	4—8	15	32	21	6—2	3/4 to 1 1/2
16 3/4	5—3	18	39	25	7—1	3/4 to 2
22 1/2	5—3	18	53	25	7—4	1 to 2 1/2
22 3/4	6—6	24	71	34	9—4	1 1/2 to 3
28 1/2	5—3	18	68	25	7—7	1 1/2 to 3
28 3/4	6—6	24	90	34	9—7	2 to 4
28 3/4	7—8	30	112	42	11—5	2 1/2 to 5
34 1/2	6—6	24	110	34	9—10	2 1/2 to 5
34 3/4	7—8	30	135	42	11—8	3 to 6
34 3/4	8—11	36	165	51	13—8	3 1/2 to 7
40 1/2	6—6	24	130	34	10—1	3 to 6
40 3/4	7—8	30	160	42	11—11	3 1/2 to 7
40 3/4	8—11	36	193	51	13—1	4 to 8

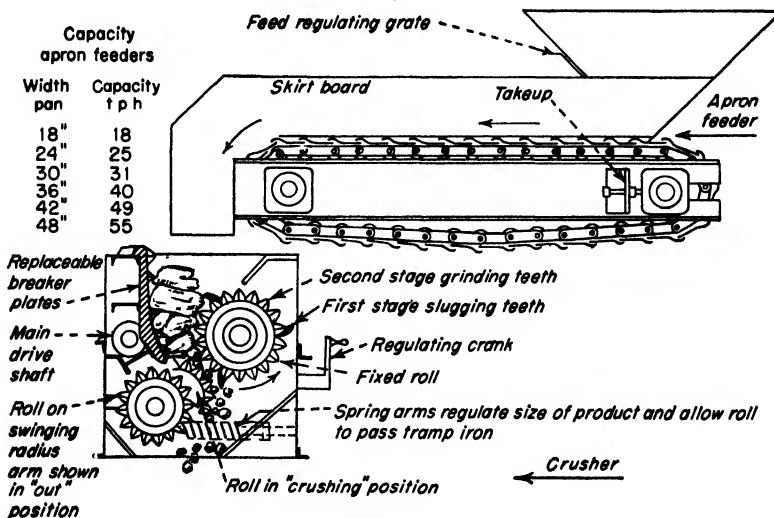


FIG. 18-10. Stephens-Adamson apron feeder and two-stage crusher. Diagram shows the two-stage action, in which the material is given a primary breaking followed by the final sizing. The lower roll is mounted on swinging radius arms and its position can be varied to regulate the size of final product. Relief springs enable the roll to open to pass tramp iron, etc.

balanced buckets, cable, sheaves, guides, and hoisting equipment. The construction is simple, and operation and maintenance costs are low. Control is either manual or automatic. Only a small ground area is required, but the pits at the receiving end are usually deep and the headroom required is high. As shown in Fig. 18-11, the coal-

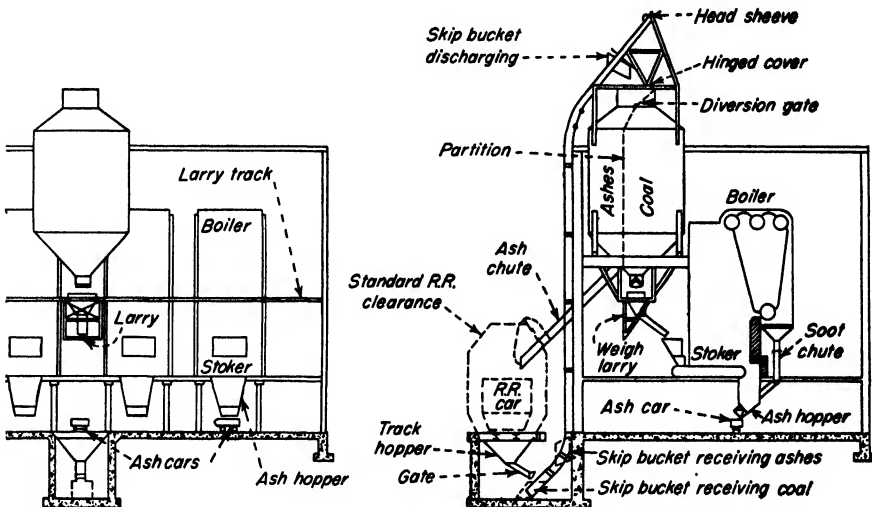


FIG. 18-11. Application of Bartlett-Snow skip hoist to plant of medium size. This system has both the coal and ashes stored in the same hopper—separation is effected by a diversion gate and a partition. In the figure the skip bucket, after having lifted the hinged cover, is shown discharging ashes into the bunker. The skip bucket is shown dotted in the alternate loading positions—for the coal and for the ash. Ashes are charged into a hand ash cart that is rolled over to the skip bucket, and unloaded. Coal is charged into the skip hoist from the track hopper and gate.

and ash-handling systems are closely integrated. Coal from the rail hopper is elevated to the bunker by a skip hoist. From the bunker the coal is distributed to the stokers by a traveling weigh larry. Small cars in the basement collect the ashes, which are dumped into the coal skip hoist. The ashes are elevated and dumped into

Table 18-4. Equipment per Rated Boiler Plant Horsepower<sup>1</sup>

Rated installed boiler hp	Coal consumption, tons /24 hr	Skip bucket, cu ft capacity	Approx capacity, tons/hr	Capacity, tons/4 hr	Storage bunker, tons	Larry size	Refuse produced, tons <sup>a</sup> /24 hr (15% of coal)
1,000	36	30	25	100	75 <sup>b</sup>	1,000 lb	5.40
1,500	55	30	25	100	75 <sup>b</sup>	1,500 lb	8.25
2,000	73	30	25	100	100	1 ton	11.00
2,500	91	40	35	140	125	1 ton	13.60
3,000	110	40	35	140	150	1 ton	16.50
4,000	146	60	50	200	200	2 tons	21.90
5,000	183	60	50	200	250	2 tons	27.20

<sup>1</sup> Bartlett & Snow.

<sup>a</sup> This figure is purposely high to act as a factor of safety.

<sup>b</sup> All figures are calculated for an average bituminous coal with average ash content. Allowances must be made for those coals whose Btu content is low, ash content is high. With railroad delivery, bunker should hold more than one carload. Bunkers marked may be smaller if truck delivery is used. Capacity figures are for 80-ft lift. If the lift is other than 80 ft, see Fig. 18-12.



a partition of the coal bunker, segregation from the coal being effected by a diversion gate at the top of the bunker. Ash chutes deposit the ashes into railway cars when desired. Yard storage can be secured by depositing the coal in a chute from the bunker and reclaiming with a portable conveyor which dumps the coal back into the rail hopper.

**Bucket Elevators.** The centrifugal discharge elevator consists of malleable iron or steel buckets spaced at regular intervals on a single chain with the usual construction. The buckets receive their load partly by scooping from the bottom and partly through a loading leg (see Fig. 18-13). The feed point is lower, loading is simpler, speeds are higher, and fewer buckets are required than for continuous types; consequently, the centrifugal types are less costly. Buckets are operated at sufficient speed so that

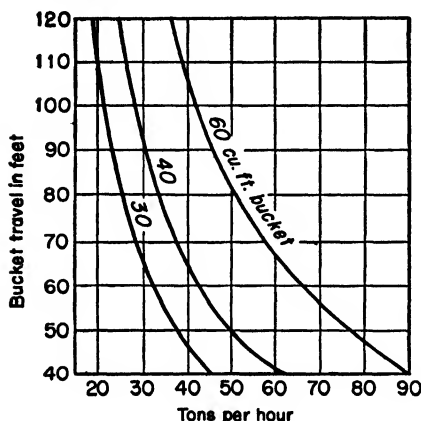


FIG. 18-12. Capacity chart for Bartlett-Snow skip buckets handling coal weighing 50 lb/cu ft. Cable speed 100 ft/min.

Table 18-5. Bucket Speeds and Head-wheel Diameters<sup>1</sup>

Head-wheel diam., in.	Spaced buckets		Head-wheel diam., in.	Spaced buckets	
	Rpm	Fpm		Rpm	Fpm
15	50 2	197	42	32 0	352
18	46 3	218	48	30 1	378
20	42 8	225	54	28 4	402
24	41 4	260	60	27 0	424
26	40 0	272	66	25 8	445
30	38 2	300	72	24 7	465
36	34 3	323			

NOTE: Averages for good centrifugal discharge and good bucket pickup.

<sup>1</sup> Stephens-Adamson.

they are discharged by centrifugal force as they pass over the head wheel. If the speed is too high, the effect of the increased centrifugal force is to throw out the coal too early so that some may fall down the elevator leg. If the speed is too low, gravity takes hold and the coal spills onto the head wheel and causes it to back-leg. It is evident that in this type of elevator the relationships of head-wheel diameter, speed, and bucket spacing must be carefully considered (see Table 18-5).

The "perfect discharge" is similar to the centrifugal except that the buckets are usually mounted between two chains making a sturdier construction. Just under the head wheel are mounted snubbing sprockets (Fig. 18-13), the slight impact of which, combined with the upending action, is sufficient to empty the bucket cleanly of sticky material such as wet coal. Since the speed is slower, the buckets are spaced closer or made larger than the centrifugal type, in order to secure the same capacity.

The continuous bucket elevator delivers good capacity at but 60 per cent of the speed (maximum 150 fpm) of the spaced buckets and will handle larger lumps than the two previously mentioned types. These buckets are so shaped that, as they pass over the head wheel, the discharging bucket utilizes the flanged back of the preceding bucket as a chute to place the material in the discharge hopper. This type is not designed for digging and must have a loading leg and hence requires greater headroom and a deeper boot than the spaced bucket. The boot must have cleanout doors to take care of coal dropped in the feeding (Fig. 18-14). This type of elevator can be operated either vertically or inclined or with single or double chain, depending on the capacity.

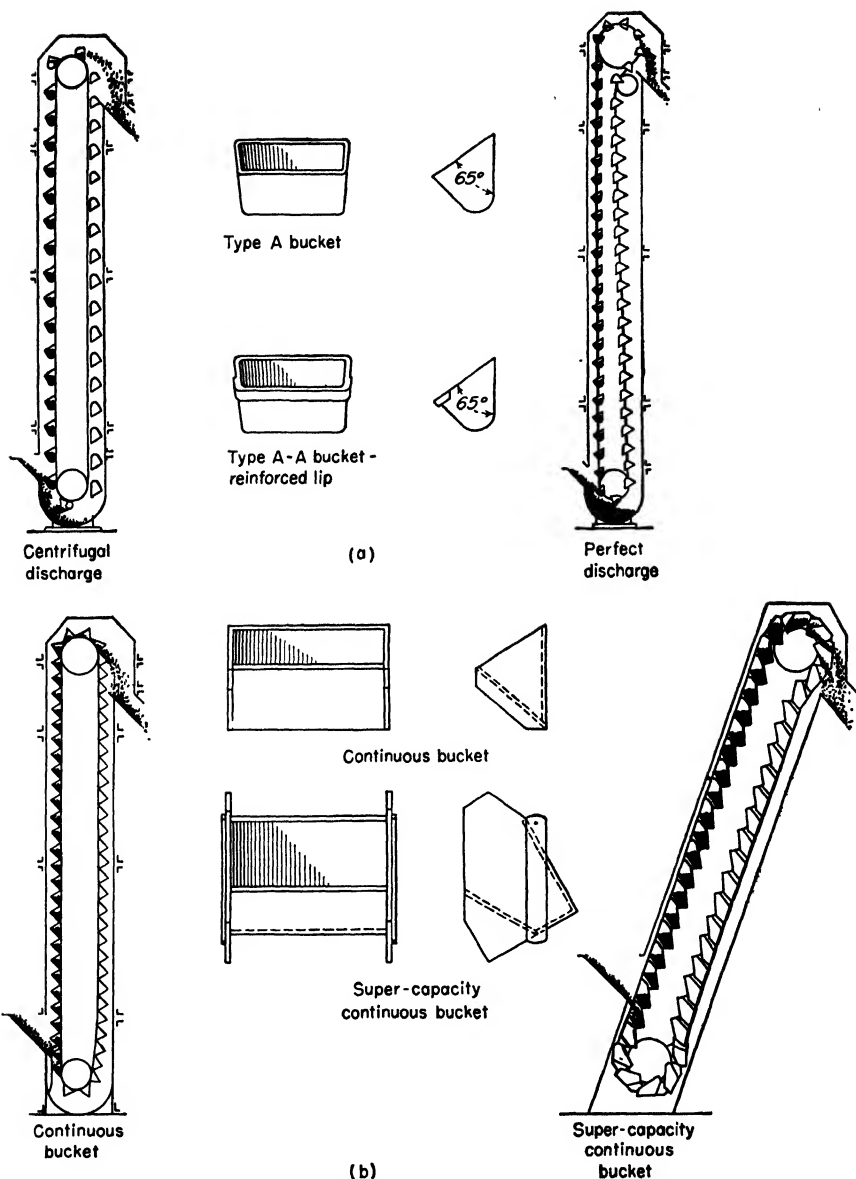
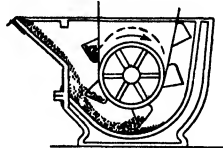


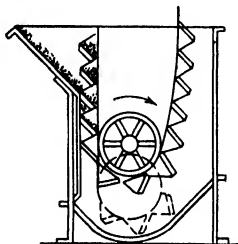
FIG. 18-13. a. Spaced bucket elevators. b. Continuous-bucket elevators. (Stephens-Adamson Mfg. Co.)

The supercapacity continuous bucket elevator handles the largest capacity of heavy lump material, such as run-of-mine coal. To reduce impact and wear in the presence of heavy loads, the speeds are comparatively low, 150 fpm. These elevators are generally operated at inclines of 35 to 70 deg for optimum loading and discharge conditions but can be operated vertically.

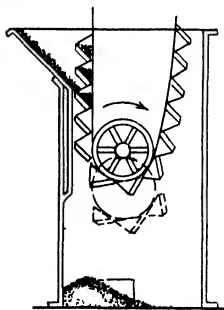
**Bucket Size.** The size of the bucket depends on the capacity required. The presence of lumps will usually dictate larger sized buckets. In the design of the elevator, care must be taken to allow for sufficient capacity to take care of peak loads. If such peaks do occur in an elevator of insufficient capacity, flooding of the boot occurs, which might result in injury to the chain or the drive. It must be noted that bucket capacity is given for the bucket level full.



(a) Spaced buckets receive part of load directly and part by scooping from the bottom



(b) Continuous-buckets are filled as they pass through loading leg, with feed spout above tail wheel



(c) Continuous-buckets in bottomless boot, with clean-out door

FIG. 18-14. Bucket-elevator loading boots. (Stephens-Adamson Mfg. Co.)

drops from the buckets may be periodically removed (Fig. 18-14).

**Horsepower required** should always be calculated for the maximum capacity to which the buckets can be loaded and the next largest motor chosen. The following formulas, according to Stephens-Adamson Mfg. Co., include normal drive and pickup losses for vertical and slightly inclined elevators.

$$\text{Spaced buckets and digging boots, hp} = \frac{TH}{500}$$

$$\text{Continuous buckets with loading legs, hp} = \frac{TH}{550}$$

Since it is usually impossible to fill the bucket in actual practice, allowance should be made for this loss in capacity in the design of the elevator. Since one side of the elevator has the buckets loaded, and the other empty, some feature of the mechanism must be included to prevent this unbalanced weight from reversing the travel when the power is off, flooding the boot and causing difficulties on the next start. Usually some form of solenoid-operated brake or a pawl and ratchet is used to prevent the back travel. Because of the large variety of standard buckets available, no attempt will be made to list them.

**Casing.** Manufacturers have available a large number of standard elevators. Where it is desirable to confine dust, catch or return back-legged material, guard the buckets, or in some cases support the drive for moderate-length elevators, steel casings in standard lengths are available. Inspection doors should be provided to allow the operator to tighten bucket bolts, check the loading, observe if any material is sticking to the return buckets (which decreases the capacity), and inspect the buckets and chain for wear.

**Loading Boots.** Boots with take-up bearings are good practice. This take-up enables the operator to maintain the proper chain tension to eliminate any chain whip. Where the buckets are fed from a loading leg only, cleanout doors must be provided so that material that

where  $T$  = tons/hr

$H$  = vertical lift, ft

For capacity, horsepower required, typical arrangements, standard accessories, working dimensions, clearances, and weights, see catalogues of Stephens-Adamson Mfg. Co., Aurora, Ill.; The Jeffrey Mfg. Co., Columbus, Ohio; Link-Belt Co., Philadelphia, Pa.; The C. O. Bartlett & Snow Co., Columbus, Ohio; Beaumont-Birch Co., Philadelphia, Pa.; and others.

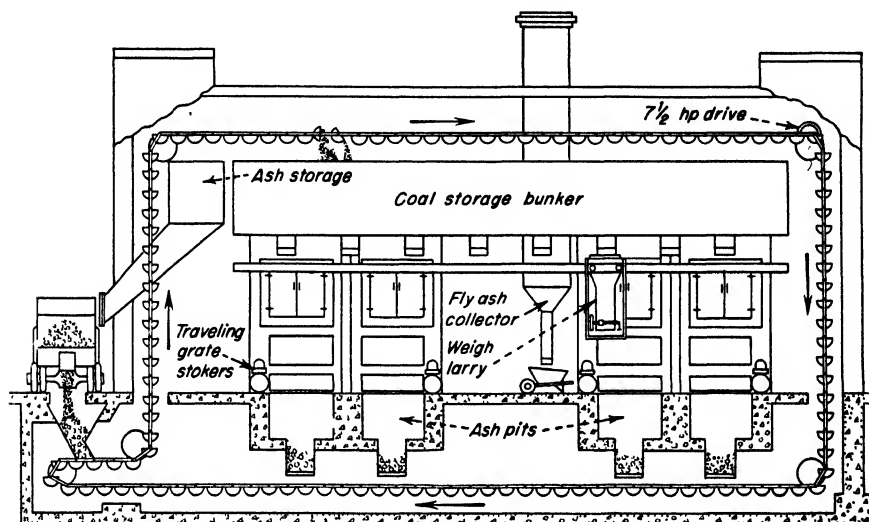


FIG. 18-15. Pivoted bucket carrier handling both coal and ashes.

*Pivoted bucket carriers* consist of round-bottom buckets pivot-mounted on long pitch chains equipped with small wheels or rollers. These wheels run on a track and hence carry the bucket. Since the bucket is pivoted above its center of gravity, it always tends to remain level whether on a vertical or horizontal run. Thus, in the same piece of apparatus the coal is both conveyed and elevated (Fig. 18-15). Because of the nature of the bucket suspension, it must be loaded and discharged on a hori-

Table 18-6. Capacities of Pivoted Bucket Carriers (Peck Type)<sup>1</sup>

Bucket pitch × width, in.	Pitch of chain, in.	Capacity of bucket, cu ft level full	Capacity, tons of coal/hr*	Speed, fpm
18 × 15	18	0.74	15-20	30-40
18 × 18	18	0.89	20-25	30-40
18 × 21	18	1.04	25-30	30-40
24 × 18	24	1.55	35-45	40-50
24 × 24	24	2.08	50-60	40-50
24 × 30	24	2.55	60-75	40-50
24 × 36	24	3.09	70-90	40-50
30 × 24	30	3.65	80-105	45-60
30 × 30	30	4.55	95-130	45-60
30 × 36	30	5.47	115-155	45-60
36 × 36	36	8.00	160-255	50-80

<sup>1</sup> Link-Belt Co.

\* Capacity based on 80 per cent actual capacity of buckets.

zontal run, which necessitates four corner sprockets. In order to discharge the bucket, some form of stationary or moving tripper is used. Because of the positive nature of the discharge, both coal and ashes can be handled on the same system. In order to avoid spillage at the loading points, the buckets are equipped with overlapping edges, so that the material cannot fall between buckets. Since the speeds are low (30 to 80 fpm, depending on the size of the buckets) and the construction heavy, these units run relatively trouble-free and have relatively long life but are higher in first cost than the other bucket types. Power required is lower than that required for any other bucket type and is dependent on the size and arrangement.

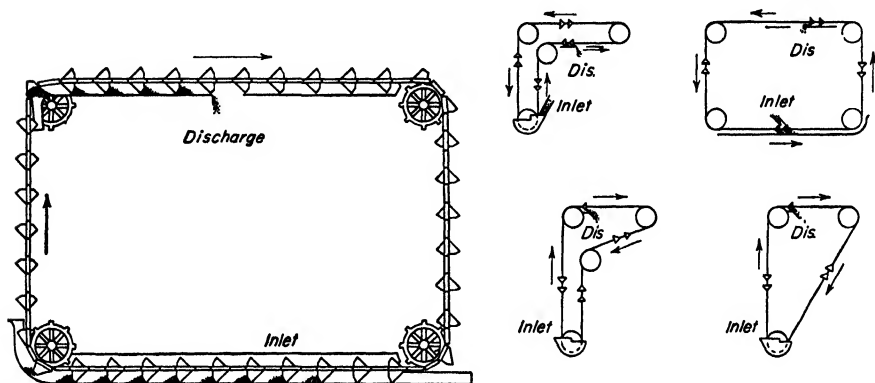


FIG. 18-16. Beaumont-Birch V-bucket gravity-discharge elevator conveyor. Various arrangements.

The V-bucket carrier gravity discharge consists of V-shaped buckets firmly fastened to a double chain which carry the coal (crushed or lump) up vertical or inclined runs and push it in a trough on the horizontal run. This type of equipment will load at any point on a horizontal run or from a loading boot (Fig. 18-16), and discharge is effected on the horizontal run through openings in the trough. Because of the higher speed (100 to 120 fpm) the V bucket has greater capacity than the pivoted bucket. However, this type cannot discharge over a head wheel but only on a horizontal run. It consumes more power on a horizontal run than any other bucket type and because of the sliding action is not suitable for ash handling.

Table 18-7. Capacity of V-bucket Gravity Discharge<sup>1</sup>

Size of bucket, in.	Gauge of plate	Weight of bucket, lb	Capacity of coal, lb	Water capacity, cu in.	Net coal capacity, tons/hr at 100 fpm	
					Bucket spacing, in.	
					27	36
16 × 16	No. 10	26	30	1,024	40	30
16 × 20	3/16 in.	43 5	37 5	1,280	50	35
20 × 20	3/16 in.	50	58	2,000	75	60
20 × 24	3/16 in.	60	70	2,400	90	70

<sup>1</sup> Beaumont Birch

**"Zipper" enclosed-belt conveyor elevator** (Fig. 18-17) folds the specially built belt around the material to be handled and locks it into a completely enclosed tube by means of a zipper at the top of the belt. Material is then distributed with no leakage or dust. Along the carrying run, the teeth are locked together and can be pulled apart only by greatly distorting them. At feed and discharge points, the teeth are

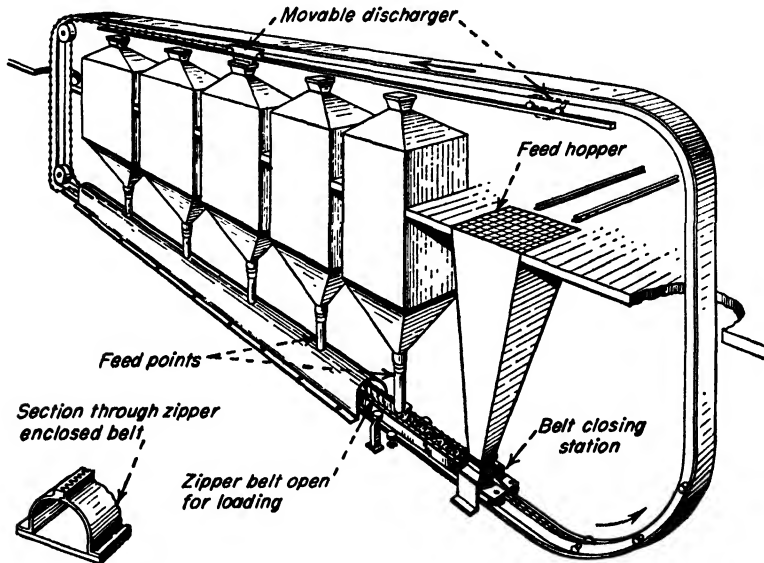


FIG. 18-17. Zipper enclosed-belt conveyor elevator. (Stephens-Adamson Mfg. Co.)

spread apart by the action of the rollers, so that they lock and unlock freely and with little friction. For shapes of conveyors involving horizontal or sloping runs, the horsepower requirements are similar to belt conveyors. For elevating, the horsepower is only slightly more than that required to overcome gravity and is therefore lower than most types of elevators. Information as to applications, sizes, capacities, and clearance can be secured from the Stephens-Adamson Mfg. Co., Aurora, Ill.

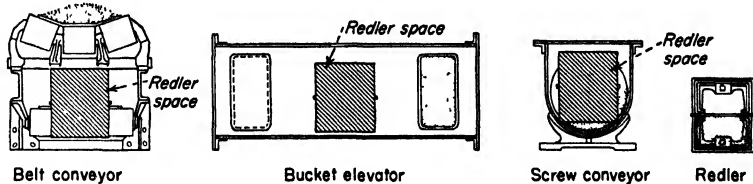


FIG. 18-18. Comparative space required for various types of conveyors of the same capacity. (Stephens-Adamson Mfg. Co.)

**Flight Conveyors.** There are two general types of flight conveyors, the skeleton and the solid or scraper. The **skeleton** or **Redler** type conveys and elevates by mass action (Figs. 18-18 and 18-19) which moves pulverized or small lump material horizontally, vertically, on incline, or around bend corners. This action takes place in a totally enclosed dust-tight casing of very compact design that permits large tonnages to be handled in small spaces. Because of the choke-feed or self-feeding action the

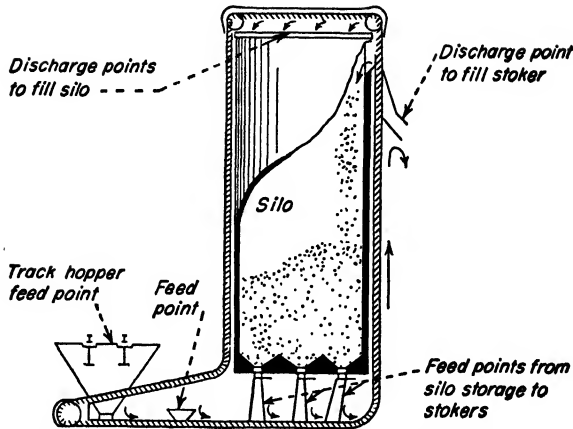


FIG. 18-19. Storing and reclamation system. Coal is dropped into the track hopper where the conveyor carries it either to the stoker spout or into the silo which allows the coal to be carried to the stoker chute.

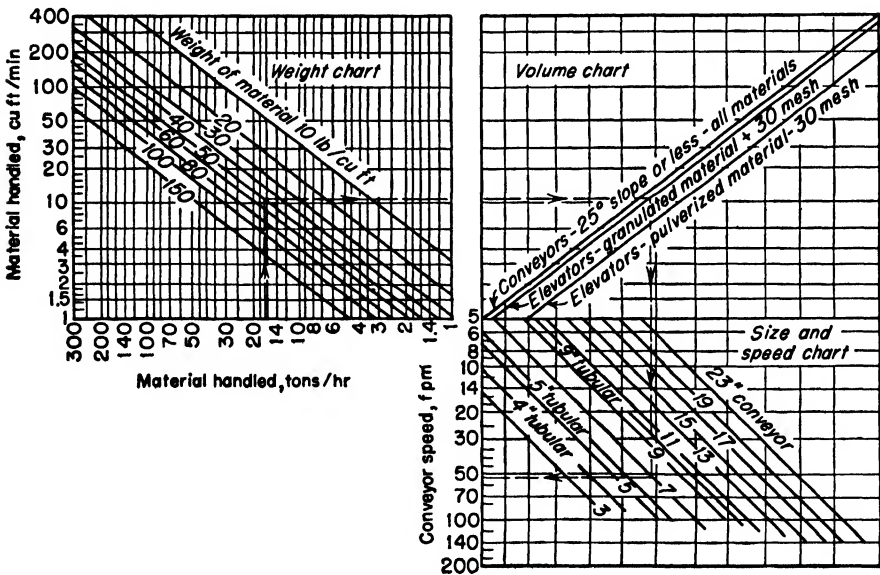


FIG. 18-20. Redler capacity chart. Example: Enter weight chart at 17 tons/hr and move upward to diagonal indicating coal at 50 lb/ft<sup>3</sup>. Move horizontally into volume chart indicating 12 ft<sup>3</sup>/min. The line is continued until the diagonal "Elevators—granulated material," where it drops vertically to the diagonal "7-in. conveyor or elevator" in the size chart. Then left to the recommended speed of 50 fpm. The same procedure shows a 9-in. size at 35 fpm or a 5-in. size at 90 fpm. (Stephens-Adamson Mfg. Co.)

casing takes on a load to fill it and no more, eliminating the need for separate feeders. The deep pits that some types of elevating equipment require are not necessary, only enough room for gravity feed. Sizes vary from the 3 in. up to large units handling hundreds of tons per hour. Discharge can be effected on either the vertical or horizontal run, as indicated in Fig. 18-19. For capacity see Fig. 18-20.

The skeleton flights or links are detachable and are designed so that the connecting joint is flexible enough to move readily around corners. There is no friction of metal against metal in the carrying run, as the material being conveyed and elevated completely surrounds the flight and forms a cushion between the flight and the casing. The amount of metallic contact of the remainder of the run depends on the installation arrangement.

Information concerning Redler applications, clearances, dimensions, etc., may be secured from the Stephens-Adamson Mfg. Co., Aurora, Ill.

**Scraper Type.** Two types are in general use, the single chain and the double chain. The single chain is used generally for crushed coal; the double chain will handle run-of-mine of quite large lumps (Fig. 18-21). A vertical plate, fastened to the chain, moves along a trough and drags the coal along the trough. Discharge is effected by means of gate-operated openings in the trough. This type is rugged and will work under conditions of weather and lack of operational care that would be damaging to the belt conveyor. Where the headroom is lacking for a belt tripper, the flight con-

**Table 18-8. Sizes, Capacities, and Horsepowers of Flight Conveyors<sup>1</sup>**

Flight	Lumps <sup>a</sup>		Horsepower <sup>b</sup>		Capacity, tons of coal/hr			Type
	Max	Avg	Anthracite	Bituminous	Anthracite		Bituminous at 30°	
					Horizontal to 27	at 30°		
10 × 4	3	1½	3 0	.	30	23	Single-strand flight conveyor, using malleable-iron flights; for anthracite coal	
10 × 4	3	1½	3 5	.	30	23		
12 × 5	3½	1¾	4 0	. .	46	35		
12 × 5	3½	1¾	4 5	.	46	35		
15 × 5	4	2	5.0	. .	62	47		
10 × 4	3	1½	2 5	3 7	30	23	30	Single-strand flight conveyor, using straight or curved flights with malleable-iron wearing shoes
10 × 4	3	1½	3 0	4 2	30	23	30	
12 × 5	3½	1¾	3 6	5 3	46	35	46	
12 × 5	3½	1¾	3 7	5 4	46	35	46	
12 × 5	3½	1¾	4 1	5 8	46	35	46	
15 × 6	4½	2½	5 9	8 4	67	50	67	
15 × 6	4½	2½	5 4	7.9	67	50	67	
18 × 6	5	2¾	6 8	9 8	80	60	80	
18 × 6	5	2¾	6.2	9 3	80	60	80	
14 × 6	4½	2½	3 9	6 3	60	45	60	Single-strand flight conveyor, using steel flights carried by rollers
19 × 8	5½	3	6 3	10.6	100	75	100	
16 × 8	8	4	7 6	11 6	110	95	110	Double-strand flight conveyor using steel roller chain with steel flights
16 × 8	8	4	7 9	11 9	110	100	110	
20 × 10	10	6	10 8	17 2	170	150	170	
20 × 10	10	6	10 3	16 7	170	140	170	
24 × 10	12	8	12 5	20 0	200	180	200	
24 × 10	12	8	11 9	19 5	200	165	200	
30 × 12	14	10	17 0	28 4	300	260	300	
30 × 12	14	10	16 3	27 6	300	260	300	
36 × 12	16	12	20 0	33 6	360	315	360	
36 × 12	16	12	19 3	33 0	360	315	360	

NOTE: Chain speed 100 fpm.

<sup>1</sup> Link-Belt Co.

<sup>a</sup> Maximum lumps not to exceed 10 per cent of total volume.

<sup>b</sup> Horsepower at head shaft, based upon coal at listed capacities, for 100-ft horizontal-center conveyors. Horsepowers for inclines are figured separately. Add 15 per cent for each cast-tooth gear reduction and 10 per cent for each cut-tooth gear reduction.



veyor has the advantage because of its small height. Also, the flight can operate from the horizontal up to 45 deg of incline. Because of the scraping action, the flight consumes more power than the belt conveyor, and there is wear of the trough because of the scraping.

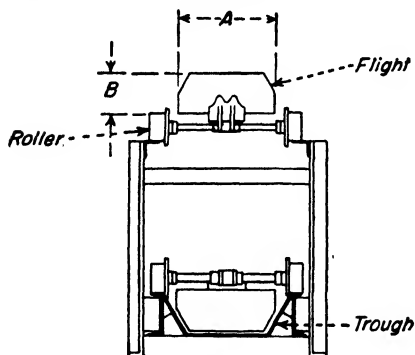


FIG. 18-21. Single-strand flight conveyor. This type uses steel flights carried on rollers that keep the flight from touching the trough where the coal is conveyed.

The belt conveyor has few moving parts, involves a minimum of friction, and requires less power than any other type of power-driven conveyor. The only relative motion between the coal and the belt is on loading and discharge, provided that the belt is not inclined over 15 to 20 deg so that there is a minimum of wear and maintenance. Because of their small height, with the exception of the belt tripper, only a small amount of headroom is required. The belts come in a variety of widths and can be operated at a variety of speeds, and a wide variety of capacities is therefore available. They are especially well suited to large capacity and long-distance conveying and hence

find wide application in central-station coal handling.

Belt conveyors must not be operated at too steep an incline or the material will slide back, causing belt abrasion. Temperatures above 150°F cause excessive shrinking, burning, and deteriorating of the belt. Continued exposure to sunlight will also cause deterioration, as well as extremes of heat and cold. The belt should also be kept free of grease and oil because the ordinary belt cannot resist their action. Care should be taken that the pulleys are accurately aligned, for misalignments throw the belt to one side or the other, causing side fray of the belt. Coal should not be allowed to fall on the top of the return belt, as it then is crushed between the belt and the pulley, causing rapid wear or in extreme cases cutting or piercing of the belt.

**Maximum Inclines for Belt Conveyors.** The maximum slope at which a belt conveyor can handle coal depends on the condition of the material, the size and shape of the particles, and the method of loading. Large lumps can be carried up steeper slopes if they are embedded in sufficient percentage of fines. A uniformly loaded belt will carry up a steeper incline than an intermittently loaded belt, as the uniform load tends to steady the belt and prevent backsliding.

**Belt Material and Selection.** The carcass of the belt consists of plies of high-grade canvas embedded in rubber. Depending on the material being handled, the rubber cover protecting the carcass can be made of various thicknesses. Since the belt represents about 40 per cent of the installation investment, extreme care must be exercised in the selection of the proper width, speed, thickness, and cover. Also, the belt is the element that handles the material and is usually the only item requiring renewal. In order to have sufficient tensile strength to pull the fully loaded belt, the cross section must be designed with a sufficient number of plies of canvas. On the other hand, belts containing too many plies will not trough readily, and without proper troughing the belt does not train properly. Excess belt thickness produces high bending stresses where the belt travels around the end pulleys, and this tends to

Table 18-9. Maximum Angle of Incline for Belt Conveyors<sup>1</sup>

Fuel	Deg
Coal, anthracite.....	16
Coal, briquettes.....	12
Coal, domestic size.....	18
Coal, run-of-mine.....	18
Coal, slack.....	20
Coke, run-of-oven.....	18
Coke, screened.....	18
Coke, breeze.....	20
<sup>1</sup> Stephens-Adamson Mfg. Co.	

Table 18-10. Minimum Belt Widths for Lumps and Recommended Idler Spacing<sup>1</sup>

Width of belt, in.	Type of carrying idler	35-lb material			50-lb material			75-lb material			Spacing return of idlers <sup>1</sup>	
		Idler spacing	Sized, in.	Un-sized, in.	Idler spacing	Sized, in.	Un-sized, in.	Idler spacing	Sized, in.	Un-sized, in.	Type	
											41	71
14	40	5'6"	2	3	5'6"	2	3	5'0"	2	3	10	10
	80	5'6"	2	3	5'6"	2	3	5'0"	2	3	10	10
	70	5'6"	2	3	5'6"	2	3	5'0"	2	3	10	10
16	40	5'6"	2½	4	5'6"	2½	4	5'0"	2½	4	10	10
	80	5'6"	2½	4	5'6"	2½	4	5'0"	2½	4	10	10
	70	5'6"	2½	4	5'6"	2½	4	5'0"	2½	4	10	10
18	40	5'6"	3	5	5'6"	3	5	5'0"	3	5	10	10
	80	5'6"	3	5	5'6"	3	5	5'0"	3	5	10	10
	70	5'6"	3	5	5'6"	3	5	5'0"	3	5	10	10
20	40	5'6"	3½	6	5'6"	3½	6	5'0"	3½	6	10	10
	80	5'6"	3½	6	5'6"	3½	6	5'0"	3½	6	10	10
	70	5'6"	3½	6	5'6"	3½	6	5'0"	3½	6	10	10
24	40	5'6"	4½	8	5'0"	4½	8	4'6"	4½	8	10	10
	80	5'6"	4½	8	5'0"	4½	8	4'6"	4½	8	10	10
	70	5'6"	4½	8	5'0"	4½	8	4'6"	4½	6	10	10
30	40	5'0"	7	12	4'6"	7	12	4'0"	7	12	10	10
	80	5'0"	7	10	4'6"	7	10	4'0"	7	10	10	10
	70	5'0"	7	8	4'6"	7	8	4'0"	7	8	10	10
36	40	5'0"	8	16	4'6"	8	16	4'0"	8	16	10	10
	80	5'0"	8	14	4'6"	8	14	4'0"	8	14	10	10
	70	5'0"	8	8	4'6"	8	8	4'0"	6	6	10	10
42 <sup>a</sup>	40	4'6"	10	20	4'6"	10	20	4'0"	10	17	9	9
	80	4'6"	10	12	4'6"	10	12	4'0"	10	12	9	9
	70	4'6"	6	6	4'6"	6	6	4'0"	6	6	9	9
48 <sup>a</sup>	40	4'6"	12	24	4'0"	10	20	3'6"	10	17	9	
	80	4'6"	12	12	4'0"	10	10	3'6"	8	10	....	8
	70	4'6"	6	6	4'0"	6	6	4'0"	....	..	....	8
	59	4'6"	12	24	4'0"	12	24	4'0"	12	24	10	
54 <sup>a</sup>	40	4'0"	12	24	4'0"	10	20	3'6"	10	17	9	
	59	4'0"	13	26	4'0"	13	26	4'0"	13	26	Δ10	
60 <sup>a</sup>	40	4'0"	12	24	4'0"	10	20	....	....	..	9	
	59	4'6"	14	28	4'6"	14	28	4'6"	14	28	Δ10	

<sup>1</sup> Link-Belt Co.<sup>a</sup> Larger lumps can be carried at less than normal belt speeds, or somewhat narrower belts may be used at reduced capacity or higher speed.

Δ Use type 60 return idlers.

Un-sized material: 90 per cent less than maximum size shown; 75 per cent not larger than one-half maximum.

separate the piles or even break the outer plies. However, sufficient plies must be designed into the belt to prevent sagging between the idler pulleys.

The belt must be **loaded** in such a fashion that impact and abrasion are reduced to a minimum. The ideal way is to have the material move in the same direction as the belt and at the same speed of the belt at the loading point. These conditions will not damage the belt. It is important that the belt train properly; i.e., the belt must be

**Table 18-11. Capacities for Various Belt Widths, Speeds, and Material<sup>1</sup>**  
(In tons per hour)

Width of belt, in.	Weight /cu ft of material	Belt speed, fpm										Cross section of load, sq ft	Cu ft /hr at 100 fpm	
		100	150	200	250	300	350	400	450	500	550			600
14	35 50 75	11 16 24	17 24 37	23 32 49	28 41 61	34 49 73							0 108	648
16	35 50 75	15 21 31	22 32 47	29 42 63	37 53 79	44 63 94							0 140	840
18	35 50 75	19 27 40	28 41 61	38 54 81	47 68 101	57 81 121	66 95 142	76 108 162					0 180	1,080
20	35 50 75	24 34 51	35 51 76	47 67 101	59 84 127	71 101 152	83 118 177	94 135 202					0.225	1,350
24	35 50 75	35 50 75	52 75 112	70 100 150	87 125 187	105 150 225	122 175 262	140 200 300	157 225 337	175 250 375			0 333	2,000
30	35 50 75	57 81 121	85 121 182	113 162 243	142 202 304	170 243 365	198 284 425	227 324 486	255 364 546	284 405 608			0 540	3,240
36	35 50 75	82 117 176	123 177 264	165 235 352	205 293 440	247 352 529	288 413 616	329 470 705	370 528 792	412 587 881	452 646 968	494 705 1,057	0 783	4,700
42	35 50 75	114 162 244	171 244 365	227 325 487	284 406 609	341 487 731	398 568 853	455 650 975	512 730 1,097	569 812 1,219	625 893 1,340	682 975 1,462	1 083	6,500
48	35 50 75	154 220 330	231 330 495	308 440 660	385 550 825	462 660 990	539 770 1,155	616 880 1,320	693 990 1,485	770 1,100 1,650	847 1,210 1,815	924 1,320 1,980	1,466	8,800
54	35 50 75	200 285 427	300 427 640	400 570 855	500 712 1,070	600 855 1,282	700 997 1,497	800 1,140 1,710	900 1,282 1,925	1,000 1,425 2,137	1,100 1,567 2,350	1,200 1,710 2,565	1,900	11,400
60	35 50 75	252 360 540	378 540 810	504 720 1,080	630 900 1,350	756 1,080 1,620	882 1,260 1,890	1,008 1,440 2,160	1,134 1,620 2,430	1,260 1,800 2,700	1,386 1,980 2,970	1,512 2,160 3,240	2,400	14,400

<sup>1</sup> Link-Belt Co.**Table 18-12. Recommended Maximum Belt Speeds<sup>1</sup>**  
(In feet per minute)

Material to be conveyed	Belt width, in.										
	14	16	18	20	24	30	36	42	48	54	60
Crushed material, nonabrasive coal	300	300	400	400	500	500	600	600	600	600	600
Lump material, nonabrasive coal	300	300	400	400	400	450	450	450	450	500	500
Crushed material, abrasive coke	300	300	400	400	500	500	500	500	500	500	500

NOTE: Select belt speed within normal operating range to permit use of minimum belt width for lump size and tonnage required.

*Suggested operating speeds:*

300 fpm is approximate minimum speed for handling wet material.

150 to 250 fpm is speed to use for discharge plows.

300 fpm is speed to use wherever a tripper is used.

<sup>1</sup> Link-Belt Co.

kept true on the carrying and the return runs. If the belt does not train properly and runs to one side or the other, the belt edges will wear off against frames or other obstructions and the bottom of the belt is liable to be injured by riding on the edges of troughing idlers; furthermore, the material may spill. This correct training can usually be accomplished by using self-aligning idlers spaced every 10 or 15 idlers on the carrying run, and every 20 to 30 idlers on the return run.

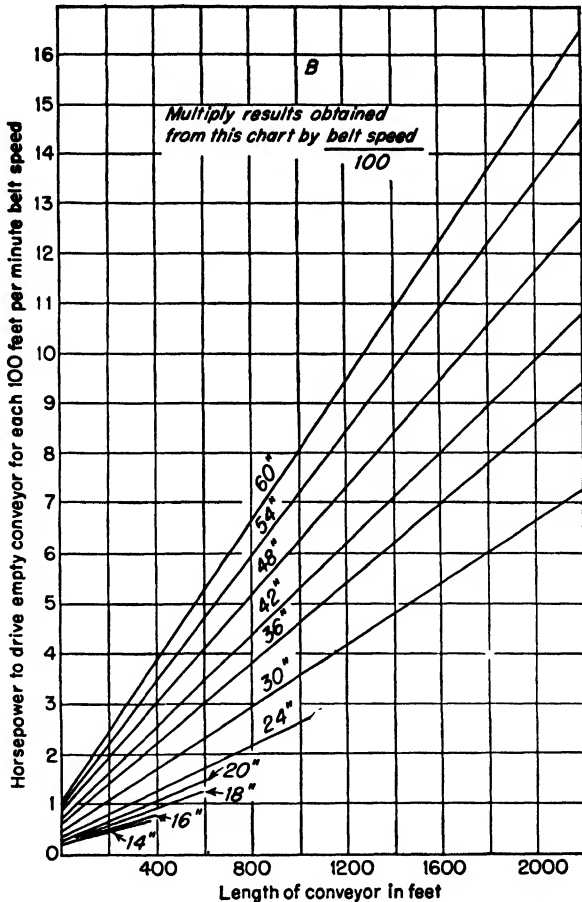


FIG. 18-22. Chart *B* to find horsepower required to drive empty conveyor. Values are based upon the use of antifriction idlers. Horsepower losses in drive not included in this chart.

The conveyor belt deteriorates more when it is not in use than when it is in operation. Direct sunlight checks the belt surface with a consequent further deterioration when water gets into the plies and freezes. Unless water does get into the plies, there is no other danger of freezing. The belt should be housed to keep sunlight from checking the belt; also the housing prevents windage loss of fine coal particles.

Inexperienced designers, misled by the apparent simplicity of the belt conveyor, have laid out systems that have given dissatisfaction to the user, which, if properly designed, could have given the utmost in economy and service. In the last analysis,

the problem of the proper belt selection should be left to the engineering department of the company supplying the installation.

**Horsepower Formulas.** The Link-Belt Co. has adopted the Goodyear Tire and Rubber Co. formulas for belt-conveyor horsepower required at the drive pulley. By

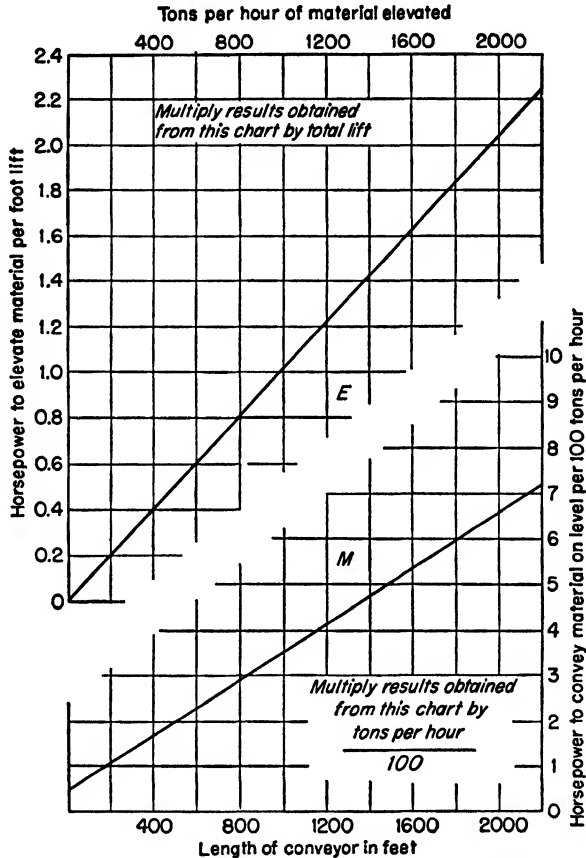


FIG. 18-23. Charts *M* and *E* to find horsepower to convey and elevate material. Values are based upon the use of antifriction idlers. Horsepower losses in drive not included in this chart.

running the belt faster, a lighter belt can be used, since the horsepower does not materially increase with the greater speed, but the torque is reduced. Modern design tendencies are to higher speeds and range from 450 to 550 fpm (with one belt operating 800 fpm), with a consequent decrease of belt thickness and an increase of belt life.

$$\text{Hp required for empty conveyor (chart } B) = \frac{C(L + L_0)(0.03QS)}{990} \quad (18-1)$$

$$\text{Hp required to convey material horizontally (chart } M) = \frac{C(L + L_0)T}{990} \quad (18-2)$$

$$\text{Hp required to elevate material (chart } E) = \frac{TH}{990} \quad (18-3)$$

$$\text{Total hp required at head shaft} = \frac{C(L + L_0)(0.03QS)}{990} + \frac{C(L + L_0)T}{990} \pm \frac{TH}{990} \quad (18-4)$$

<sup>1</sup> This is a minus value for lowering conveyors.

- where  $C$  = friction factor (see table below for values of  $C$  and  $L_0$ )  
 $Q$  = weight of moving parts, per ft of center distance (see Table 18-13)  
 $L$  = horizontal length of conveyor, ft  
 $L_0$  = length constant (see table below for values of  $C$  and  $L_0$ )  
 $S$  = speed of belt, fpm  
 $T$  = tons/hr, peak capacity  
 $H$  = vertical height or rise of conveyor, ft

Values of  $C$  and  $L_0$ 

	Friction factor $C$	Length factor $L_0$ , ft
For equipment with ordinary bearings . . .	0 050	100
For average type of antifriction idler . .	0 030	150

Table 18-13. Values of  $Q$ 

Value of $Q$ based on	Belt width, in.										
	14	16	18	20	24	30	36	42	48	54	60
Troughing idler spacing	5'0''	5'0''	4'6''	4'6''	4'0''	4'0''	3'6''	3'6''	3'6''	3'6''	3'6''
Return idler spacing	10'0''	10'0''	10'0''	10' 0''	10'0''	10'0''	9'0''	9'0''	9'0''	7'0''	7'0''
Weight of belt, lb/ft	2 5	2 8	3 5	4 5	5 0	8 5	11 0	13 0	16.0	18.0	21.0
Value of $Q$	15	16	19	21	25	34	44	50	60	69	77

NOTE: The above values are based on average operating conditions. Factor  $C$  will diminish under ideal operating conditions but will be increased with poor installation and maintenance of equipment.  $L_0$  covers a power-absorbing factor for belt, material, and terminals, independent of length of conveyor, and is expressed in additional feet of conveyor for convenience.

$Q$  consists of the weight of the revolving parts of one type 40 troughing idler divided by the spacing in feet, one type 41 return idler divided by spacing in feet, and 2 ft of average-specification conveyor belt.

Table 18-14. Trippers<sup>1</sup>

Constant	Width of belt, in.									
	14	16	18	20	24	30	36	42	48	54
Y	0 0020	0.0020	0 0026	0.0029	0.0034	0.0047	0 0060	0.0069	0.0082	0 0100
Z	0 0035	0.0035	0.0035	0.0040	0 0040	0 0050	0 0050	0.0055	0.0060	0 0070

NOTE: When a tripper is used, the horsepower required for conveyor operation is increased according to the following formula:

$$Hp = YS + ZT$$

where  $S$  = belt speed, fpm

$T$  = tons/hr, peak capacity

$Y$  and  $Z$  = constants from table

<sup>1</sup> Link-Belt Co.

In determining power required for declined conveyors, subtract from the sum of Eqs. (18-1) and (18-2) the value obtained from Eq. (18-3), for a lift in feet equal to the required drop. Total horsepower provided at head shaft for declined conveyors must never be less than the value of Eq. (18-1).

**Magnetic Pulleys.** Where it is necessary to remove the tramp iron from the coal, magnetic pulleys are used. These are usually placed as the last pulley on the head

shaft before the equipment utilizing the coal requiring iron-free coal. These pulleys are of two types, the permanent magnet and the electromagnet.

Where the belt conveyor is inclined, the belt conveyor should be provided with some form of **brake or ratchet** in case of power breakdown when the belt is loaded. This brake prevents the belt from running backward and flooding the lower end if the slope is sufficient that the force of gravity is greater than friction of the belt.

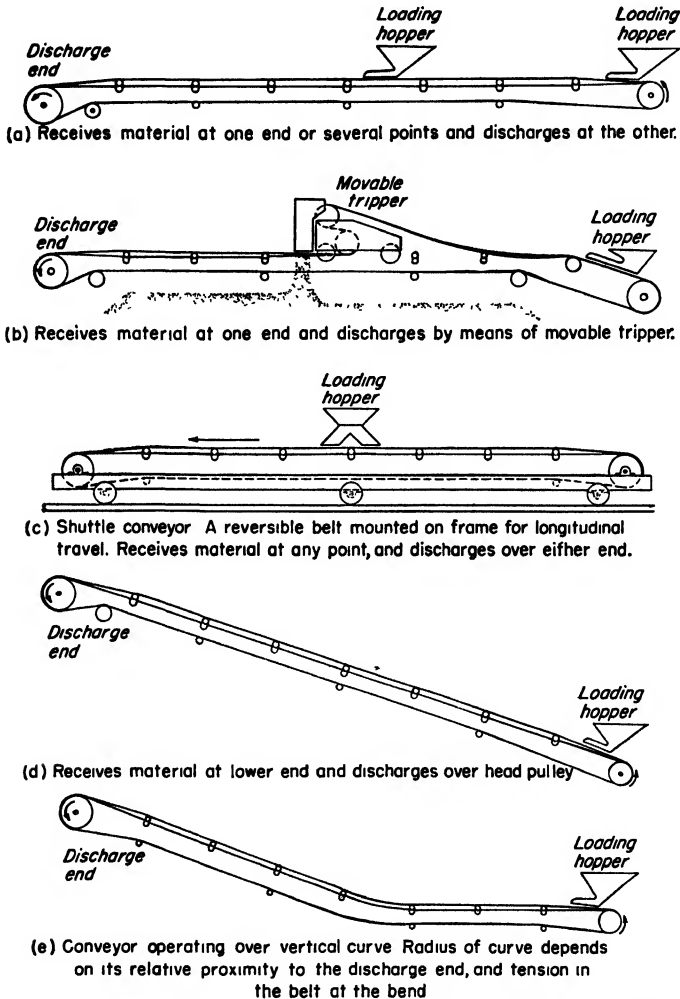


FIG. 18-24. Belt conveyors, typical arrangements. Where tramp iron is to be removed, a magnetic pulley is placed on the last pulley of the head shaft.

**Belt Trippers.** The only way that the troughed conveyor belt can discharge without a tripper is by discharging over the end of the belt. In order that the belt can discharge at any intermediate point between the end pulleys, some form of tripper must be used. If the discharge point is fixed, the tripper is fixed. As the loaded belt comes to the tripper, as in Fig. 18-24, it is bent over a pulley to duplicate the conditions at the end pulley. The coal is then discharged in the same manner as it would

be at the end pulley. This coal is projected into a chute that straddles the belt and discharges on either one or both sides as desired. If the conveyor is servicing a long bunker, the tripper is motor-driven so that the coal is evenly distributed along the bunker.

Central stations demand such large tonnages of coal that the belt conveyor is invariably used for the coal handling. Also, since belt conveyors can operate over long distances and at varying grades, they are used to bring coal from the unloading equipment directly to the coal bunkers.

For more specific data on belt conveyors refer to Link-Belt Co., Philadelphia, Pa.; C. O. Bartlett & Snow Co., Cleveland, Ohio; Jeffrey Mfg. Co., Columbus, Ohio.

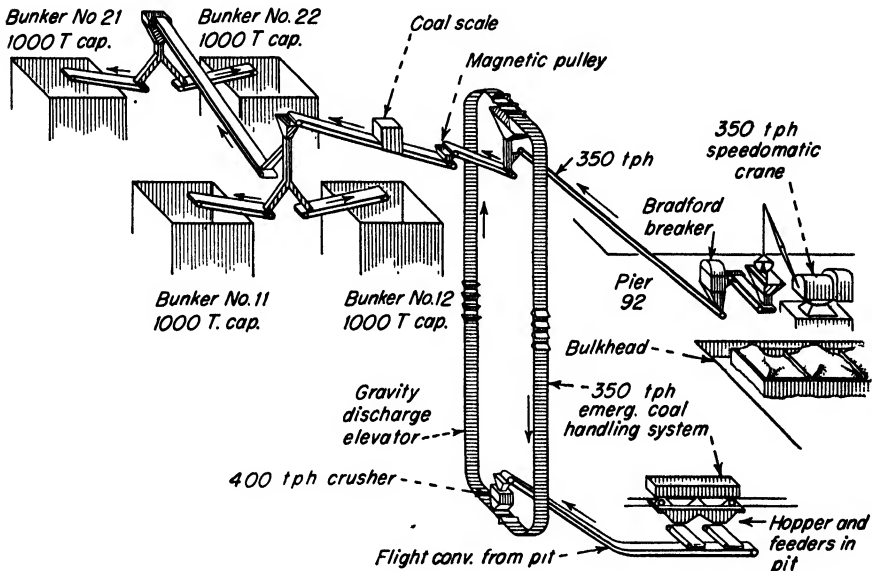


FIG. 18-25. Schematic layout of Southwark generating station coal-handling system. (Philadelphia Electric Co.)

### Central Stations<sup>1</sup>

The economical handling of coal to ensure an uninterrupted supply to the boilers is one of the major problems in the design of central stations and differs from most other design problems in the great number of variables which exist and the numerous combinations of equipment and methods which can be used. The method of receiving the coal at the plant is usually one of the deciding factors in the general layout. If coal is received by water in large lake or oceangoing vessels, rapid unloading facilities are necessary to avoid demurrage. For this purpose movable towers with large grab buckets are used. For river transportation, open coal barges are used, and it is the general practice to use stationary unloading towers with grab buckets for unloading. On the Great Lakes, the use of self-unloading vessels (Fig. 18-26) is becoming more prevalent, and this materially reduces the coal-handling equipment required.

Some central stations are located at the mouth of the mine and receive their coal directly from the mine in mine cars. Coal received by rail generally comes in hopper-

<sup>1</sup> DANIELS, GEORGE C., "Coal Handling Systems for Central Stations," presented at the semiannual meeting, Kansas City, Mo., ASME, June, 1941.



Table 18-15. Comparison of Coal-handling Costs

Plant designation <sup>a</sup>	Coal delivered by water, rail, or truck	Year installed	Capacity to bunkers, tons/hr	Cost of installation, including docks, tracks, pits, cranes, conveyors, etc.	Years represented by data	Tons coal burned/year	Load factor on coal-handling equipment	Maintenance cost, cents/ton	Operating labor, cents/ton	Total operating costs, cents/ton	Fixed charges based on 12% year, cents/ton	Total fixed and operating costs, cents/ton
A	W	1939	400	\$ 691,000	1940	124,000	3 5	1 3	5 0	6 3	67 0	73.3
B	W	1925	350	1,220,000	1937-1939	382,046	12 5	5 3	7 6	12 9	38.1	51.0
C	W	1926	250	655,000	1938-1940	547,574	25 0	4 2	4 0	8 2	14 4	22.6
D	W	1928	125	978,000	1935-1940	175,879	16 1	4 8	6 6	11 4	66.8	78.2
E	R	1939	200	360,000	1940	196,000	11 2	7 7	6 1	6 8	22.0	28.8
F	R, T	1939	125	160,000	1940	122,924	11.2	4 5	6 4	10 9	15.8	26.7
G	R	1936	100	212,000	1940	79,300	9 1	1 9	7 5	9 4	32.0	41.4
H	R	1913	75	66,000	1936-1938	109,000	16 7	2 4	5 3	7 7	7.3	15.0
I	R	1925	75	112,000	.....	217,588	33 0	2 1	4 4	6 5	6 3	12.8
J	R	1927	60	160,000	1938-1940	62,606	11 9	6 1	9.8	15 9	30 7	46 6
K	R	1928	60	164,000	1937-1939	43,860	8 3	4 9	10.1	15 0	45 6	60 6
L	R	1926	50	97,000	1937-1939	54,636	12 4	4 8	8.1	12 9	21.5	34.4
M	R	1920	40	20,000	1939-1940	40,077	11 4	3 4	6.7	10 1	6.0	16.1
N	T	1937	150	185,000	1940	275,376	21 0	.....	.....	10 6	8 1	18 7
Avg....	.....	.....	.....	.....	.....	.....	14 6	3 0	6 7	10 3	27.2	37.6

<sup>a</sup> Description of system.

- A. Coal delivered on dock by self-unloading lake boats, gantry crane to storage, or to belt conveyors to plant.  
 B. Gantry crane from lake boats to storage, or by car and belt conveyor to plant. Auxiliary drag-line storage.  
 C. Clamshell from river barges to belt conveyors to plant or to Lidgetwood storage.  
 D. Clamshell from ocean steamers or barges to belt conveyors, to plant or to drag-line storage.  
 E. Cars discharge by gravity into pit, to belt conveyors, to plant or to drag-line storage.  
 F. From cars by gravity to pit, to belt and bucket elevator, to drag-line storage or to plant by belt.  
 G. From cars by gravity to pit, to belt and bucket elevator, to drag-line storage or to plant by belt.  
 H. Stationary tower with clamshell bucket from cars to distributing belt. Locomotive crane for storage.  
 I. Locomotive crane with clamshell bucket from cars to pit, to chain and bucket elevator, to scraper conveyor.  
 J. Cars discharge by gravity into pit, to belt and bucket elevator, to scraper conveyor. Locomotive crane for storage.  
 K. Cars discharge by gravity into pit, to belt and bucket elevator, to scraper conveyor. Bridge crane for storage.  
 L. Cars discharge by gravity into pit, to belt and bucket elevator, to scraper conveyor. Bridge crane for storage.  
 M. Cars discharged by gravity to shallow pit, to inclined scraper conveyor, to bunkers. Storage by portable conveyor.  
 N. Cars dump into pit, to skip hoists, to belt distributors. Storage by locomotive crane and bulldozer.

bottom cars, but in some localities coal is shipped in flat-bottom cars which may or may not be provided with dump bottoms. Such cars must be unloaded with grab bucket or by means of a car dumper. Delivery by truck from nearby mines is becoming more prevalent, and provisions for such delivery have been made at many plants.

The complexity of the problem prevents the detailed description of even representative systems.

A comparison of **coal-handling costs** is shown in Table 18-15. The installation costs given are the original costs, plus additions, less retirements. They include all the investment chargeable to coal-handling equipment, except the coal bunkers in the plant, and include such items as coal docks, turning basins, unloading towers, cranes, conveying and elevating equipment, coal crushers, railroad tracks, and track hoppers.

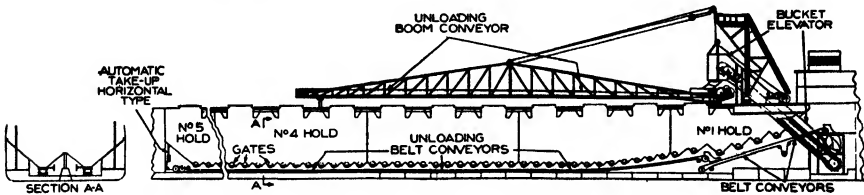


FIG. 18-26. Self-unloading vessel. The holds are emptied by discharge gates at their bottoms. Coal drops onto conveyor belts that carry it to a bucket elevator that hoists it to the boom unloading conveyor. On unloading the boom is swung out and the coal is discharged alongside of the vessel. (*Stephens-Adamson Mfg. Co.*)

The **load factors** on the coal-handling equipment given in Table 18-15 are based on the total coal consumed per year and the handling capacity to the bunkers.

#### Car-unloading Methods<sup>1</sup>

The capacity of the coal-handling equipment when receiving coal by rail is fixed largely by the speed at which cars can be emptied, which is determined by the size of the coal, by whether it is wet or dry, and by the type of cars. In some localities coal is received only in hopper-bottom dump cars. Other localities may obtain coal only in flat-bottom cars or in cars of several varieties. A grab bucket is ideal to use for flat-bottom cars, but not for hopper-bottom cars or for cars with cross bracing.

When a  $1\frac{1}{2}$ -cu yd **grab bucket** with a locomotive crane or overhead bridge is used, a 50-ton flat-bottom car can be unloaded in approximately 20 min. Allowing time for switching cars, the unloading capacity would probably not exceed 100 tons per hr continuously, and one man would be required on the crane and one on the car.

When **dumping free-flowing coal** from 70-ton hopper-bottom cars into a pit of ample size and length to dump the car at one setting, the average unloading speed including switching will approximate 200 tons per hr. Fine coal  $\frac{3}{8}$  in. or less, when wet, will reduce the speed of unloading, even with four men in the car, to 100 tons per hr or less.

Reliable capacity over 100 tons per hr when handling fine screenings, especially when wet, must be obtained by means of car unloaders or car dumpers. The "Accelerator" for unloading hopper bottom cars is shown in Fig. 18-27. The dump gates in the car are opened and the accelerator screws are revolved, digging themselves into the coal until the bottom of the car is reached, whereupon the screws are reversed to expedite the flow of coal. With this device, two 70-ton cars are unloaded per hour with one operator and one or two cleanup men in the car, when unloading into a small-capacity hopper. With a large track hopper, permitting continuous operation of the

<sup>1</sup> DANIELS, GEORGE C., "Coal Handling Systems for Central Stations," presented at the semiannual meeting, Kansas City, Mo., ASME, June, 1941.

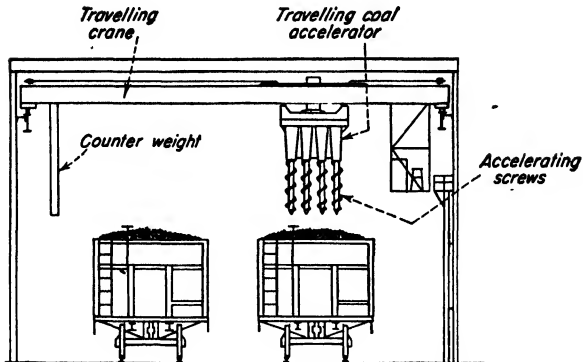


FIG. 18-27. Coal accelerator. Indicated is the mechanism by which the material accelerator is moved across railroad tracks to accelerate the removal of material on either of several tracks. Also indicated is the mounting of supporting beams on rails by which the accelerator is moved lengthwise along the car. (*Stephens-Adamson Mfg. Co.*)

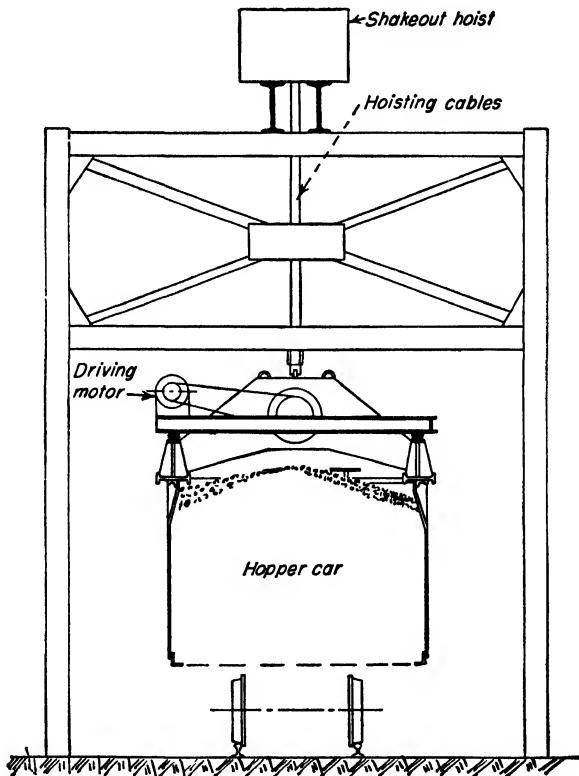


FIG. 18-28. Car shakeout. The car shakeout is lowered to the top of the car. The vibration of the shakeout loosens the coal which flows down through the hopper doors.

accelerator, a 70-ton car can be unloaded in 20 min. The accelerator is fairly efficient in handling frozen coal, provided that the coal surrounding the hopper doors is removed by hand or some other means.

**The car shakeout** unloads the loaded railroad car by applying vibration to the top of the car. The unit illustrated in Fig. 18-28, is manufactured by the Robins Conveyors, Passaic, N.J., in one standard size only. It is powered by a 20-hp motor and operates at a speed of approximately 1,500 rpm. The vibration is obtained by the use of counterweights at each end of the shaft. Stroke amplitude is approximately  $\frac{5}{32}$  in.

Unloading time varies with the type and condition of the material. For example, coal which is rather dry usually will be unloaded in 2 to 3 min.

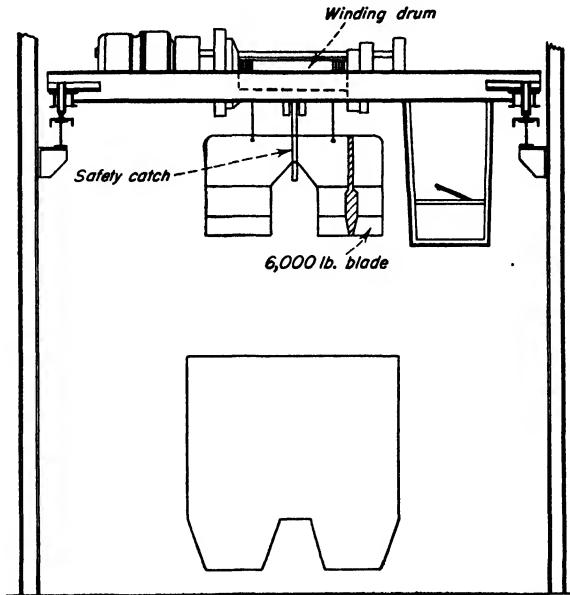


FIG. 18-29. Coal displacer, "guillotine" type. The blade is dropped on the compacted or frozen coal. When the blade is not in use it is hung from the safety hook or catch.

With respect to frozen material, some heat must be applied to the bottom of the car if freezing has penetrated more than 2 or 3 in. This heat can be supplied by a pit between the rails or by the use of small portable oil burners. With the assistance of this heat for from 10 to 30 min prior to unloading, the car shakeout will unload cars frozen on the top and along the sides and the bottom to a depth of 8 to 10 in. It will not unload a car which is frozen throughout the entire mass of material.

A coal displacer of the "guillotine" type is shown in Fig. 18-29. This consists of a 6,000-lb blade hung from a gantry crane. The car is moved under the blade, which is dropped down repeatedly on the compacted or frozen coal until it is loosened.

Capacities greater than those mentioned must be obtained by means of **car dumpers** (Fig. 18-30), which, with two men, will unload coal cars of any size and kind at the rate of one every 3 or 4 min. Frozen cars of coal present a difficult problem and cannot be handled readily with the car dumper unless they are previously thawed out or the coal is broken up.

Illustrated in Fig. 18-30 is the car dumper. In this unit, a 40-hp motor is sufficient for unloading 20 cars per hr, up to 100 tons capacity each; or, by increasing the size

of the motor, the dumper will handle 30 cars per hr, if they can be moved on and off the dumper rapidly enough. This type of equipment must be made very rugged and dependable, since they are too costly to be installed in duplicate to take care of breakdowns. For physical specifications of the equipment, consult Link-Belt, Philadelphia, Pa.; Wellman Engineering Co, Cleveland, Ohio; and others.

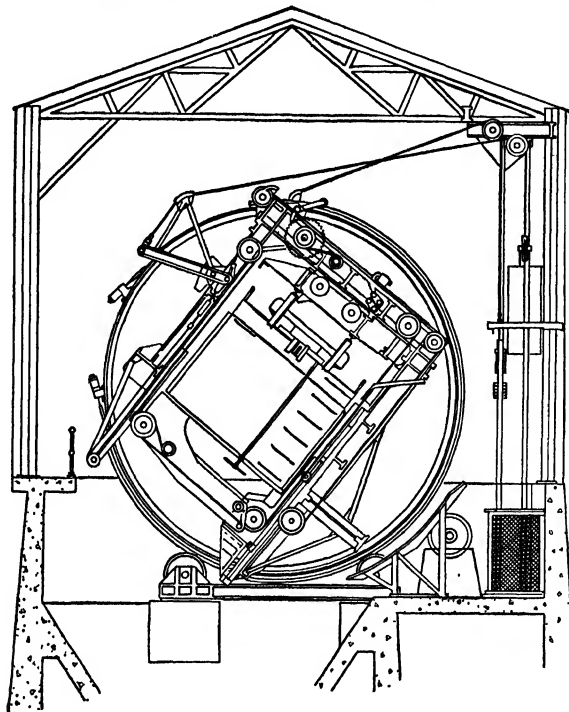


FIG. 18-30. Car dumper.

#### Unloading Frozen Coal<sup>1</sup>

One of the most vexing problems facing industrial plants is that of unloading frozen coal. While the severity of freezing can sometimes be alleviated by chemical treatment,<sup>2</sup> it often happens that coal arrives in a thoroughly congealed condition. In such cases, a relatively inexpensive yet effective means of unloading the cars is provided through the use of thawing pits. As properly constructed, they employ an indirect radiant-heating method that minimizes any damage to railroad cars during the operation. One or more pits may be installed, depending upon the number and types of cars that may require simultaneous treatment.

The thawing pit consists essentially of a shallow combustion chamber, installed between the tracks, the refractory linings of which are heated to irradiance by the flames from two oil burners which impinge upon the side walls of the pit. The heat from the walls rises up and through the car hoppers without direct flame contact. Pits may be equipped with either high- or low-pressure oil or gas burners, according to local conditions. Housing structures are not required; thus there is no restriction to normal traffic over the tracks. Such pits are frequently used in conjunction with a car shakeout to improve the efficiency of unloading.

<sup>1</sup> Thawing Pits, *Utilization*, February, 1949.

<sup>2</sup> See section on Freezeproofing Treatment, Chap. 16.

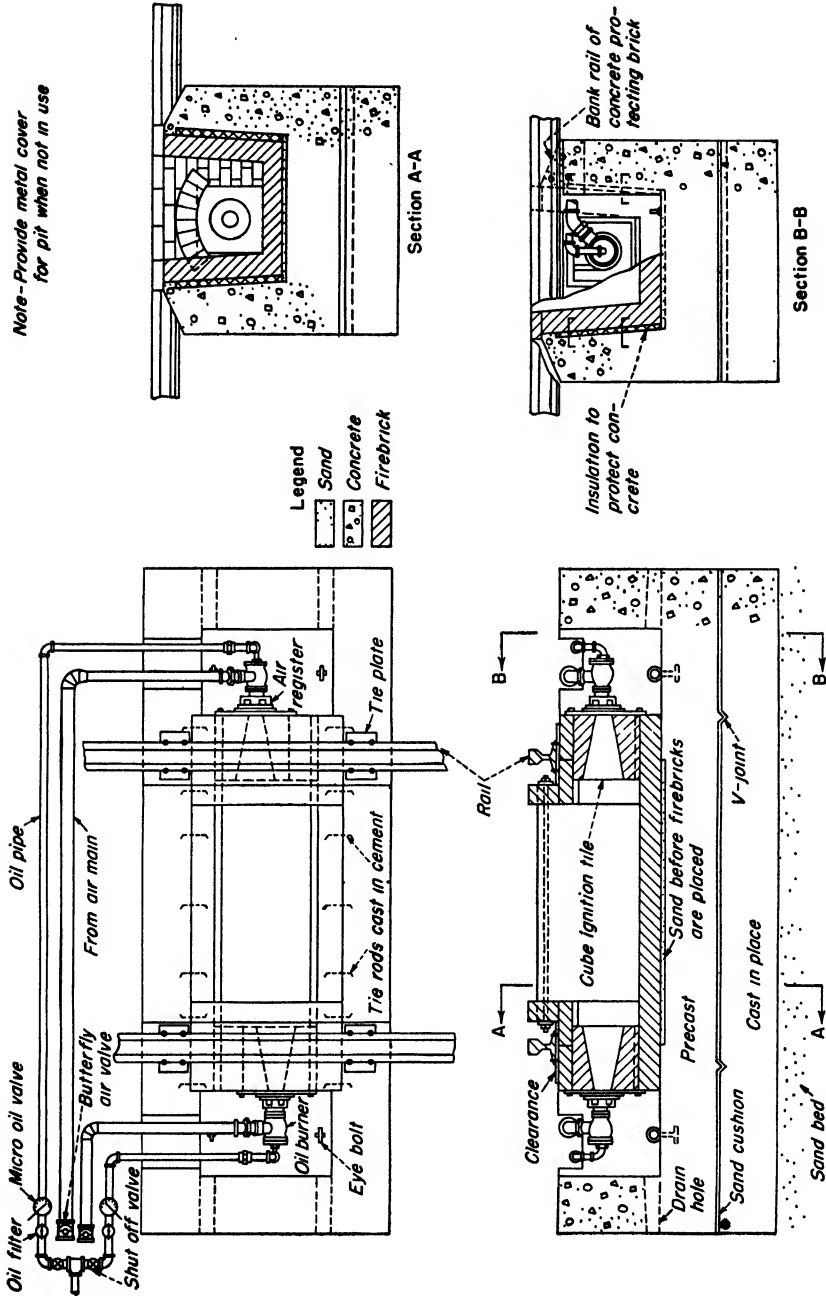


Fig. 18-31. Hauck coal-car thawing pit (patent pending) with Hauck low-pressure air type oil burners.

Fuel consumption and thawing time are subject to considerable variation according to the type and size of coal, its moisture content, the degree of freezing, and the weather. A probable fair range of oil consumption is 8 to 15 gal per 50-ton car. Time will vary from 20 min to 1½ hr under average conditions.

A typical thawing pit, as designed by the Hauck Mfg. Co., Brooklyn, for their low-pressure oil burners is as shown in Fig. 18-31. Table 18-16 shows typical test results from such an installation.

**Table 18-16. Car Thawing-pit Oil-burner Performance Summary<sup>1</sup>**

(Total cost per car, \$2.68. Total cost per ton, \$0.0489)

Train load	Weather temp (windy), deg F	No. of cars	No. of tons	Thawing time, min	Oil consumption			Oil cost/ car <sup>a</sup>	Oil cost /ton	Time cleaning (test cars only), hr	Hand torch time, hr	Labor cost/ car	Labor cost/ ton <sup>a</sup>
					Oil level, in.	Oil used, gal	Avg /car, gal						
1	15	7	393 8	57	5½ <sub>16</sub>	74 9	10 7	\$1 50	\$0 0266	1	1 9	\$0 58	\$0 0103
2	25	8	408 6	111	9½ <sub>16</sub>	142 4	17 8	2 49	0 0488	1 5	3 7	0 91	0 0178
3	30	6	330 8	56	4½ <sub>16</sub>	69 4	11 5	1 62	0 0294	1	1 9	0 68	0 0122
4	30	5	253 2	62	4¾ <sub>8</sub>	64 7	12 9	1 81	0 0358	0	2 1	0 59	0 0116
Total		26	1,386 4	286 11	23¾ <sub>8</sub>	354	13 6	\$1 90	\$0 0357	3 5	9 6	\$0 78	\$0 0132
Avg					0 918	13 6	13 6			0 13	0 33		

NOTE: Labor time based on actual testing period and costs based on \$1.40 per hour. Motor power estimated at 43 kw/hr for the cars tested. Freezing depth about 3 and 4 in., much deeper in dump hoppers. Coal was wet enough to drip heavily when being thawed.

<sup>1</sup> Report from an electric public utility in Indiana using eight Hauck thawing pits, Jan. 15, 1949.

<sup>a</sup> Hand-torch oil included in pit burner oil. Fuel \$0.14 per gallon.

### STORAGE OF BITUMINOUS COAL<sup>1</sup>

**Effect of Storage on Coal Characteristics.** The greatest hazard in the storage of coal is spontaneous combustion; the least hazard for the high-ranking Eastern coals is loss in heating value and degradation in size due to slacking. Caking characteristics of some coals may be lessened because of storage.

Studies by the U.S. Bureau of Mines, and confirmed in the field, have shown that the **loss in heating value** for Eastern bituminous coals will seldom exceed 1 per cent the first year or 2 per cent in 2 years. For low-rank Western coals, the loss in heating value may be 2 to 3 per cent the first year and over 5 per cent in 3 years. The effect upon anthracite is as discussed separately in Chap. 3.

Little difficulty, if any, should be experienced from the **slacking** of Eastern coals in storage; considerable difficulty may be experienced with low-rank Western coals.

Strongly caking coals tend to become **less caking** after storage, because of oxidation. For chain-grate stokers, storage may improve the performance of certain coals on the border line of acceptance. For pulverized-coal firing and spreader stokers, storage should have little or no effect. For underfeed stokers, efficiencies might be adversely affected if firing practices are not altered to meet the change in burning properties.

**Storage of the Several Sizes.** Industrial sizes of coal can be stored for indefinite periods if careful storage-pile methods are used and the top and sides are sealed with an airtight coating of asphalt or road tar. For periods of 1 year or less, the suggested multiple-layer procedure permits the safe storage of industrial sizes other than mine run without sealing.

**Storage of mine-run coal** should be avoided unless it can be withdrawn continuously after the airtight seal is broken. Periodic withdrawal leads to fire hazards.

<sup>1</sup> Storage of Coal, *Ohio Coal Association Research Bull.*, Cleveland, Ohio, 1949.

**Double-screened sizes** (bottom size  $\frac{3}{4}$  in.) may be stored for long periods if segregation is avoided, thus allowing essentially unrestricted flow of air through the pile.

### Procedure and Methods of Storing Coal

**Storage Site.** Preparation of the storage site is the first step in the successful storage of coal. In many respects it is the most important as it is the starting point which often determines the sequence of events leading to the economical or costly storage and recovery of coal.

Adequate drainage is essential, and the ground should be graded to drain moisture away from the pile. Low spots should be filled with earth and compacted rather than filled with cinders, which permit access of air at the base of the pile. All materials more combustible than coal should be removed, and if the storage site contains structural columns or upright members, they should not be included within the pile as they provide a perfect flue for localized access of air and moisture.

**Multiple-small-conical-pile Method.** If the amount of coal to be stored is small, or if it is not practical to own and operate material-moving equipment, only double-screened coal should be stored. To provide free access of air, the bottom size should not be less than  $\frac{1}{2}$  in., preferably  $\frac{3}{4}$  in., and the storage pile should be formed by a multiple number of small conical piles. By overlapping the small piles, segregation will be minimized. If a clamshell is used, it should be lowered near the surface of the pile to ensure a minimum drop and roll of the coal. The height of the pile need be limited only by the length of the crane boom. If a dump truck is used, the depth of the storage pile should not exceed 6 ft, owing to less control over segregation. No attempt should be made to compress the pile other than the weight of the coal itself. In the case of dump trucks, planks about twice the width of the rear tires should be provided to avoid having the truck wheels ride directly on the coal when building the pile depth higher than the truck body. The success of the multiple conical pile is free access of air to remove the heat of oxidation as rapidly as it is generated.

Do not attempt to store coal from two different beds in the same pile. Avoid storing fresh coal in a pile containing old coal.

**Horizontal Multiple-layer Method.** When industrial steam sizes of coal are to be stored in large amounts, only the horizontal multiple-layer method of building the storage pile should be considered. The object of the multiple-layer method is to mix thoroughly the various sizes of coal in all areas of the pile, thus minimizing the movement of air through the pile and the absorption or loss of moisture.

Success or failure of the multiple-layer method is dependent upon adequate material-moving equipment and the conscientiousness of the individuals doing the work. The importance of avoiding size segregation within the pile cannot be too strongly emphasized. Any procedure which falls short of doing the job correctly is vulnerable to a chain of events which can cause pile heating.

**To avoid segregation** and to ensure bulk density, the layers should not exceed 2 ft in thickness. The weight of the bulldozer has little effect upon compacting the pile, since only the top few inches of coal receive the weight of the "cats," which seldom exceeds 10 psi. If layers thicker than 2 ft are graded, segregation is likely to occur. Layers less than 2 ft are preferable owing to improved mixing. (See Figs. 18-32 and 18-33.)

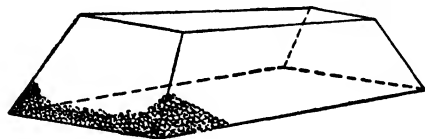


FIG. 18-32. Proper shape for large coal-storage pile. When storing subbituminous or lignite the total height should not be over ten ft.



To avoid absorption of moisture and to ensure drainage from the surface, the pile should be crowned. The top of the pile should be symmetrical to avoid large quantities of water running off in localized spots, resulting in deep gulleys and considerable washing of coal from the sides of the pile.

Exposure to winds appears to have a greater effect upon the access of air into the pile than chimney effect owing to pile height. For this reason, well-graded and compacted slopes are of more importance than height. The slopes of the pile may be



Correct



Incorrect

FIG. 18-33. Cross section of correct and incorrect storage piles. (Ohio Coal Association.)

winds should be treated somewhat more heavily for greater protection against the access of air.

**Coating Materials.** Cutback asphalts of the MC-1 or MC-2 grades are often used but require heating to 140°F to reduce viscosity for spraying. Asphalt emulsions of the AE-3 or AE-4 grades have air-sealing properties equal to the MC grades and are often preferred because they do not require heating and are more elastic after setting. The AE-4 grade is preferable owing to its characteristics of quick water separation and superior coating properties. In the event the capping cracks from settling, the cracks can be patched by hand spraying. To take up the tackiness and to fill the voids, the capped pile should be covered after spraying with a thin layer of fine coal. This is usually done by hand with a shovel.

**Temperature Observations in Storage Piles.** Large storage piles require daily checks for hot spots; small piles should be checked once a week.

Areas developing heat can be detected by the appearance of the coal under different weather conditions. In wet weather the hot area is detectable by the rapid drying, and the much lighter color of the coal above the hot spot. Streams of vapor on a cold day or a day of high humidity, and the odor of gas are further indications of heating or of air entering the pile.

Locating the hot spot may be done by probing with iron rods and testing its temperature with the hand. If the hand cannot be held on the rod after being in contact with the coal at the hot spot and quickly withdrawn, it indicates that the temperatures are at the danger point. When the pile is large and the hot spot is deep within the pile or in an awkward location, or if there are indications of several areas in danger of firing, the pile may be fireproofed by sealing the top and sides with an airtight coating of asphalt or road tar, as has been described. Preventing air from entering the pile

be compacted by cutting back, starting at the bottom, which will condition the sides to resist both access of air and moisture.

**Airtight Sealing of Coal Piles.** If the coal pile is to be permanent (1 year or more) or if mine-run coal is to be stored, the top and sides should be covered with an airtight seal of asphalt or road tar. This can be applied by spraying equipment similar to that used by road departments. For large storage piles the top can be capped, using a tank wagon equipped with rear spray nozzles, and the sides sprayed by the use of a hose and hand nozzle. Small piles may be capped by hand spraying only. A covering or cap  $\frac{1}{8}$  in. thick, requiring about 1 gal of asphalt per 10 sq ft of area has been found satisfactory. The sides exposed to prevailing

will stop further heating and actually put out the fire at locations having temperatures in excess of the danger point.

Table 18-17. Capacities of Coal Piles<sup>1</sup>

Bituminous  
B = 36 deg

Anthracite  
B = 27 deg

Bituminous  
B = 36 deg

Anthracite  
B = 27 deg

$$\text{Tons (2,000 lb)} = \frac{H^3}{20}$$

$$\text{Tons (2,000 lb)} = \frac{H^3}{10}$$

$$\text{Tons/ft} = \frac{H^2}{30}$$

$$\text{Tons/ft} = \frac{H^2}{20}$$

Height,  
ft

Diam  
of base

Tons  
(2,000 lb)

Height,  
ft

Diam  
of base

Tons  
(2,000 lb)

Height,  
ft

Tons/ft

Tons/ft

5	14 3	6.2
6	17 1	10 8
8	22 8	25 6
9	25 7	36 4
10	28 6	50.0

5	19 7	12 5
6	23 6	21 6
8	31 5	51 2
9	35 4	72 9
10	39 4	100 0

5	.83	1.25
6	1 2	1 8
8	2 1	3 2
9	2 7	4 0
10	3 3	5.0

12	34 2	86 4
15	42 9	168 7
18	51 4	291 6
20	57 2	400 0
22	62 9	532 4

12	47 2	172 8
15	59 1	337 5
18	70 8	583 2
20	78 8	800 0
22	86 6	1,080 0

12	4.8	7 2
15	7 5	11 2
18	10 8	16 2
20	13 3	20 0
22	16 1	24 2

25	71 5	781 2
28	80 0	1,097 6
30	85 8	1,350 0
35	100 1	2,143 7
40	114 4	3,200 0
50	143 0	6,750 0

25	98 5	1,562 0
28	110 3	2,200 0
30	118 2	2,700 0
35	137 9	4,280 0
40	157 6	6,400 0
50	197 0	12,500.0

25	20 8	31 2
28	26 1	39 2
30	30 0	45 0
35	40 8	61 2
40	53 3	80 0
50	83 3	125 0

<sup>1</sup> Lank-Belt Co.

### Equipment for Storing Coal

**Bin Storage.** With increased plant size, manual coal-handling costs are prohibitive and hand-firing is replaced by stoker-firing. Sized or crushed coal is burned more readily on the stoker since the bed is more uniform and the coal is burned with less waste. The coal can be purchased sized, but it is advisable to have a crusher for stand-by. In case of emergency, when sized coal cannot be secured and only run-of-mine is available, the crusher is good insurance. In addition, where the run-of-mine can be secured very cheaply, the crusher becomes a good investment. When the run-of-mine prices rise the plant then switches over to sized coal. Also, the sized coal is handled with greater facility in the elevators, hoppers, chutes, and spouts because of decreased clogging. Where feasible, the covered bin or silo has the following advantages:

1. Small ground space
2. Closeness to track storage
3. Protection from weather (dry coal is less likely to clog spouts), degradation, and theft
4. Low handling costs since the coal is handled only once

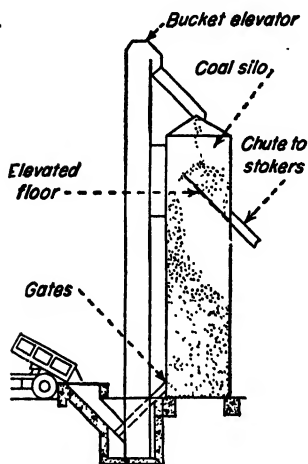


FIG. 18-34. A simple system for small plants receiving coal by truck. Provides a live-storage capacity of approximately 20 tons and a dead storage of 100 tons which is reclaimed by means of a chute to the elevator boot.

5. Not necessary to run coal machinery continuously
6. Reserves readily available in case of breakdown of machinery or delivery

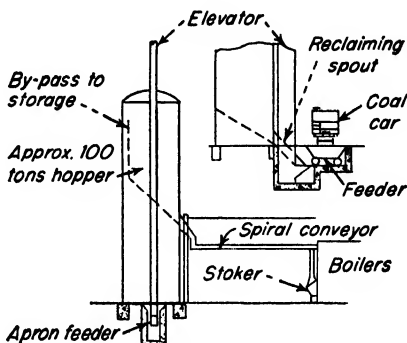


FIG. 18-35. For plants of moderate capacity receiving coal by rail. Apron feeder beneath hopper regulates feed to elevator. Provides live capacity of approximately 100 tons and a dead storage of 150 tons, reclaimed by means of chute to elevator boot. A spiral conveyor is used to deliver coal to stoker.

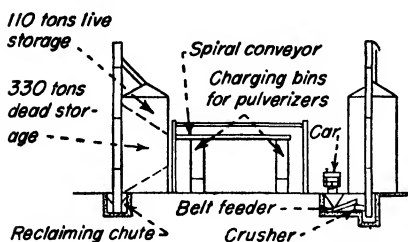


FIG. 18-36. For plants using pulverized fuel. Provides a live storage of approximately 110 tons and a reserve of 330 tons reclaimed by chute to elevator.

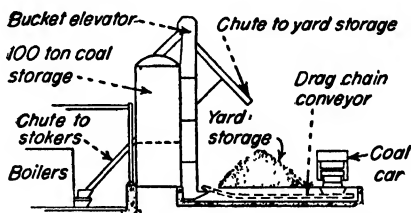


FIG. 18-37. For larger plants requiring outside storage. Provides for direct delivery from railroad cars to elevator and for reclaiming outside storage. Steel plates or planks laid across conveyor pit support outside storage and are removed to permit feed to conveyor.

Neff and Fry silos used in conjunction with Jeffry Mfg. Co. equipment are shown in Figs. 18-34 to 18-37, which indicate arrangements of small and medium plant size handling and storage.

Cylindrical storage bins require no heavy steel stiffeners and are therefore lighter in weight, simplifying the foundation problem. Bins or silos of concrete or vitrified tile (Neff and Fry, and Bartlett-Snow, Cleveland, Ohio) are not subject to corrosion

of wet coal. The cylindrical steel bunker in Fig. 18-38 (Bartlett-Snow, Stephens-Adamson Mfg., Beaumont-Birch Co.) supplies a weigh larry that passes under the gate and distributes the coal to the boilers. Coal being discharged into any bunker segregates, the fines remaining in the center, the coarser coal seeking the edges. On discharge the coal craters, and the segregation is reversed. Gas pockets in quiescent

**Table 18-18. Sizes and Capacities of Standard Silos<sup>1</sup>**

Diam of bin, (ft)	Cu ft/ft height	Capacity, tons/ft height		
		Anthracite (55 lb /cu ft)	Bituminous (50 lb /cu ft)	Coke (26 lb /cu ft)
10	78 5	2 15	1 95	1 02
12	113 5	3 12	2 85	1 47
14	154 0	4 23	3 85	2 00
16	201 0	5 52	5 00	2 61
18	254 5	6 99	6 35	3 31
20	314 1	8 63	7 85	4 08
22	380 1	10 01	9 50	4 94
24	452 2	12 43	11 30	5 87

<sup>1</sup> Neff and Fry.

coal, cause of spontaneous combustion, cannot form since the entire contents of the bunker move slightly on discharge. The tendency to pack noticeable in long bunkers is greatly reduced. Freezing of wet coal is eliminated, since the bottom of the bunker is in the boiler room.

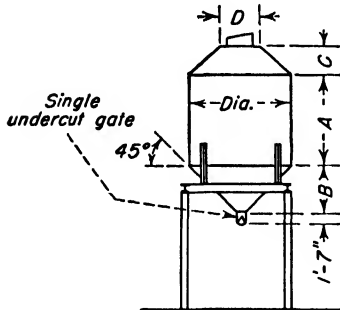


FIG. 18-38. Bartlett-Snow cylindrical coal bunker.

**Bunker Adaptor-bunker Gates.** The adaptor in Fig. 18-39 is used with cylindrical coal or ash bunkers and enables the material to be discharged through a square opening. The heavy cast-iron

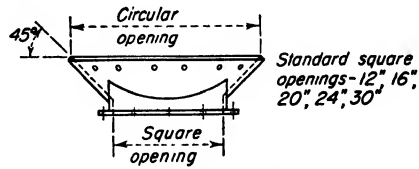


FIG. 18-39. Beaumont Birch Co. cylindrical bunker adaptor.

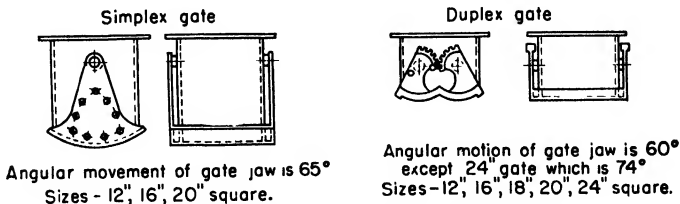


FIG. 18-40. Beaumont Birch Co. bunker gates.

construction resists abrasion where the wearing action of the coal is most severe, also it provides a rigid member to which to secure the gate. The bunker gate in Fig. 18-40 is made of cast iron to prevent abrasion. The swinging action of the gate

provides for minimum jamming, a common fault of the older slidetype gate. Both single and double gates are available.

**Suspension coal bunkers** used in medium and large plants are designed in shape to approach a catenary, a curve that will produce only tension in the plates. This condition makes for economy in design and construction. This bunker is of minimum height as compared with the cylindrical type. Where there is an unusually long row of boilers, the suspension bunker, with spouts to the stokers, is very practical.

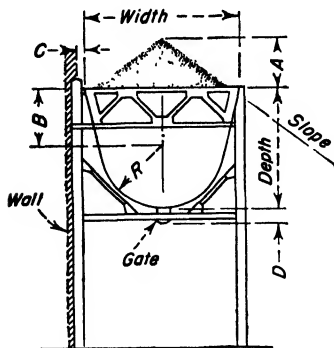


FIG. 18-41. Bartlett-Snow suspension coal bunker.

Lining is a problem as the coal is abrasive and wet coal is corrosive. Protective linings are utilized. Concrete and wire mesh were formerly used but were found to crack because of their lack of flexibility under varying loads. The cracks in the concrete allowed the corrosion to proceed unobserved. Present practice calls for several coats of acid-resisting enamel, applied hot. This coating "breathes" with load changes. An alternate is a properly designed reinforced-concrete construction which is both abrasion- and corrosion-resistant. However, this construction is expensive and productive of foundation problems as the concrete bunker is relatively heavy. Unmachined cast iron is known to be abrasion- and corrosion-resistant and is fabricated in sections to form the complete bunker (see Fig. 18-43).

**Bunker Operation.** Design of a bunker should entail more than a consideration of the total capacity; regard should be paid to trouble-free operation. The familiar

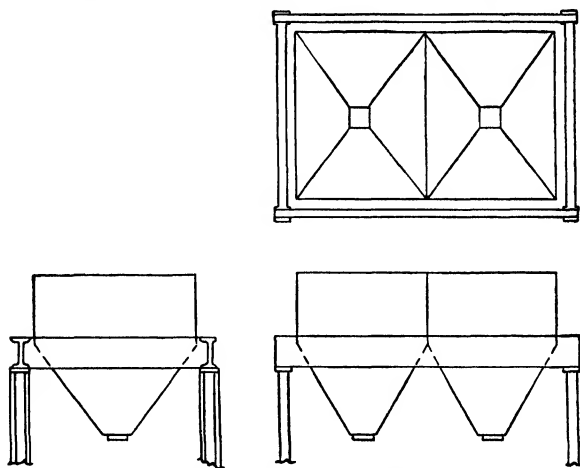


FIG. 18-42. Multiple hopper-bottom design avoids dead space but may cause arching, particularly right above outlets, where span is reduced. Agitation is the common solution. (Hahn Equipment Corp.)

suspended steel bunker suffers from dead spaces between outlets and a low discharge efficiency. Trimming and manipulation of these dead pockets is annoying and occasionally hazardous. This dead coal may also serve as the starting point for heating and spontaneous combustion of stored coal. Figure 18-42 shows a more complicated and consequently more expensive construction that nominally eliminates the

dead-storage problem—but introduces a new one, that of arching. Even crushed coal contains small lumps and fines, which under pressure of the mass above will compact and form arches over the outlets. Hammering the sides is often effective, but this solution is crude and time-consuming and often results in damage to the hopper. The best solution lies in an agitator, of substantial construction, built in the hopper throat (Fig. 18-43). This clears a space about 3 ft above the gate where the hopper dimensions are the smallest. Above this point, the increasing span of the arch weakens it; and, once the lower section has been disturbed, arching at the higher levels can hardly be sustained.

*General Bunker Details.* For the suspension bunkers, the columns should not be supported by the boiler columns as the varying loads tend to crack the boiler walls. Outlet gates should be spaced about 8 ft 0 in. apart. If practical, the bunkers should

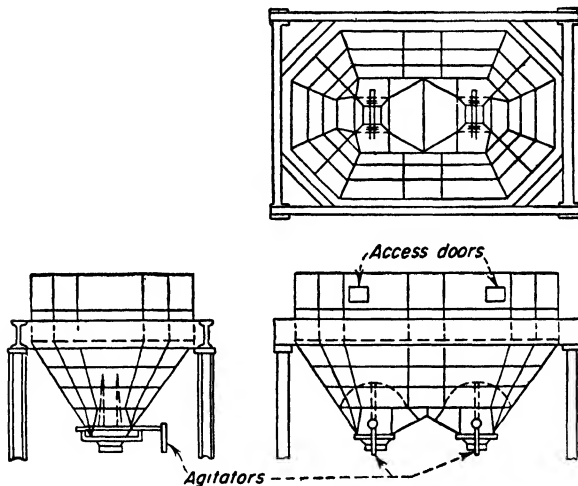


FIG. 18-43. Built of cast-iron sections to avoid abrasion and corrosion, this oblong octagon bunker weighs little more than a steel design for the same capacity and has agitators. (Hahn Equipment Corp.)

be closed over to prevent discharge of dust in the firing aisles. The location of the bunker must be such as not to interfere with boiler-tube cleaning or replacement. Distributing pipes to the boilers should not be greater than 40 deg from the vertical. In general, where weigh larries are used, care in design is necessary to provide adequate height and clearance for the larries.

*Storage Capacity.* The amount of coal to be stored in bunkers should be sufficient to take care of the boilers during shutdown for normal coal-handling-machinery repair. The question of adequate storage to provide against mine or delivery-work stoppage would be more of a company policy.

*Drag Scraper.* The equipment consists of a cable-operated bottomless scraper bucket. In the typical installation, a headpost is set up at a given point at one edge of the storage area and the incoming coal is dumped onto the ground in front of this headpost. The scraper bucket operates out from this cushion pile in radial lines toward a tail tower traveling on a track laid around the perimeter of the yard. Haulage cables, to which the bucket is attached, pass around sheaves on the tail tower and on the headpost to the haulage hoist, usually electric-driven. The operator is located where he can view the entire area. When reclaiming, the operation is

reversed, the coal being dragged back for distribution to the plant. The radial system, as well as other arrangements, are shown in Fig. 18-44.

By continually shifting the path of the bucket, the operator spreads one layer of coal on top of another. This technique serves to avoid segregation and helps to compact the pile, both of which tend to keep down storage-pile fires. This type of handling, however, promotes degradation of the coal and is particularly disadvantageous in the case of anthracite and coke in this respect. For the small and medium sized piles, the favored depths are from 15 to 20 ft, and for large piles the favored depths are from 30 to 40 ft.

**Capacities of Drag Scraper.** Handling capacities of scraper installations depend on the size of the scraper and the average distance which the scraper travels. Naturally the capacity of a given installation is greater on short spans than on long. The relative economy of the scraper is maintained on quite long spans, but it is advisable to limit the distance of bucket travel if a small scraper is used. The chart of Fig. 18-45 gives an indication of the hourly capacity in terms of bucket size and average distance of bucket travel. Specific installations may cause variations.

**Cost of Operation.** In operating costs are included the direct expenses for power, maintenance, and labor. The power consumption of an electric motor-driven installation will average about  $\frac{1}{4}$  kwhr per ton of coal handled per 100 ft of haul. The usual figure for maintenance is 1 cent per ton of coal handled. Labor costs vary with localities, and the plant activity and the amount of use of the scraper system are extremely pertinent factors. A properly designed scraper system uses one man to operate the scraper. See Fig. 18-46 for motor horsepower.

**Storage Bridge and Unloading Tower.** Illustrated in Fig. 18-47 is an unloading tower for central-station coal handling. Coal is brought to the plant by water and is unloaded by means of the 6-net-ton coal

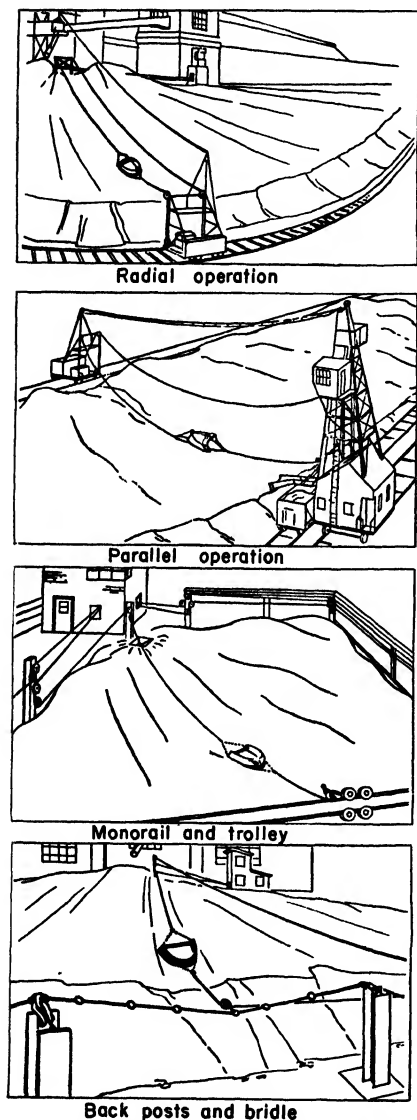


FIG. 18-44. Four general types of application of the drag scraper. (Sauerman Bros.)

bucket. If the coal is to be used immediately, it is dumped into the 55-ton hopper where a feed deposits it onto a conveyor belt that carries it to the boilers. If the coal is to be stored, it is dumped on the storage pile, which runs parallel to the pier. The

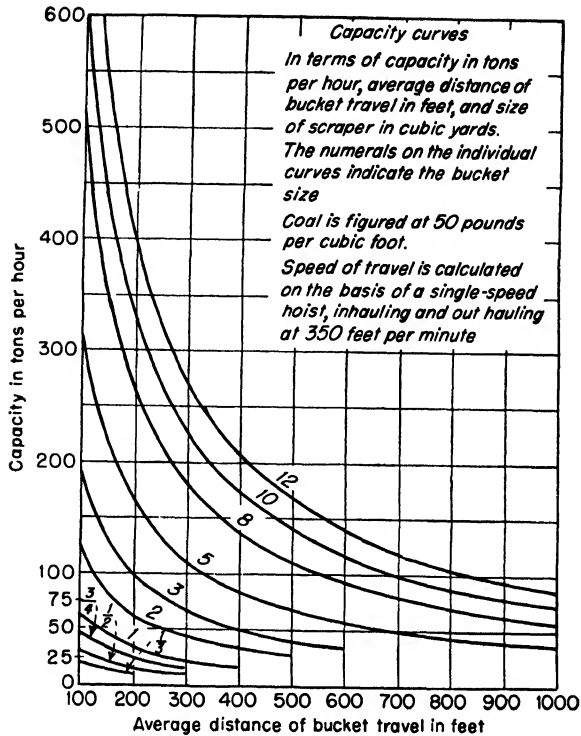


FIG. 18-45. Capacity curves of drag scrapers. (Sauerman Bros., Chicago.)

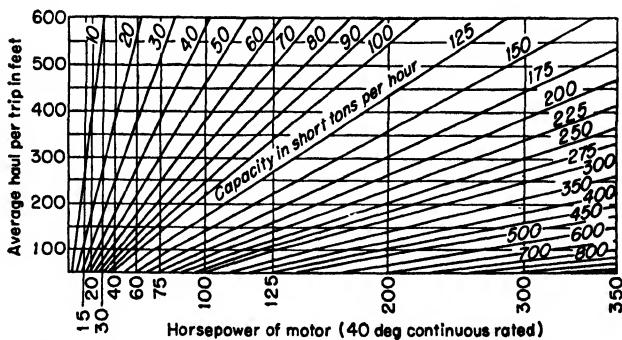


FIG. 18-46. Motor horsepower required for drag scrapers. The capacities shown in the chart are obtained at an inhaul speed of 350 fpm and an outhaul speed of 350 fpm. (Sauerman Bros., Chicago.)

whole tower runs on rails parallel to the pier to increase the volume of the storage. Reclamation is effected with the coal bucket, which scoops up the coal and deposits it in the hopper. Emergency rail-delivery facilities are also shown.

**Capacity.** In free digging and when properly operated, the machine illustrated will handle 600 net tons per hr with a hoist of 56 ft and a trolley travel of 45 ft. Unloaders and bridges are built to the specific plant design and will vary according to the plant requirement.



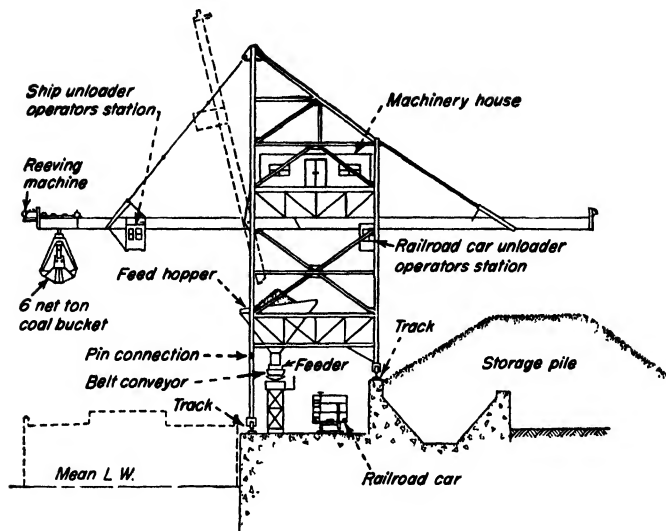


FIG. 18-47. Traveling boat-unloader tower. Material unloaded from boats or cars can either be stored or delivered directly to the bunkers by the conveyor. (Wellman Engineering Co.)

### ✓ Bulldozer and Tractor-carryall Storage

The central station must have large investments in coal-handling systems, and consequently the fixed charges are high. The use of the bulldozer and the tractor carryall has resulted in reduction of this investment and of the fixed charges. For distances up to about 150 ft the bulldozer by itself may be used economically, and for greater distances the tractor-carryall combination may be used. The bulldozer, preferably employing caterpillar treads, may be equipped with a blade set either at a right angle or at an oblique angle to the longitudinal axis of the tractor, or it may tow a carryall or scraper. The control of the carryall is accomplished from the tractor, and the leading or dumping can be done quickly or at a uniform rate as it moves along.

Many large industrial plants and public-utility plants have adopted the crawler type of tractor or the wheel-type tractor-scraper method of storing and reclaiming coal for the following reasons:

1. Fire hazard is reduced. The method results in a compact pile and virtually eliminates air pockets that contribute to spontaneous combustion.
2. Equipment investment is small compared with overhead bridges, traveling cranes, high towers, etc.
3. Equipment spread is more flexible as storage areas can readily be expanded and several areas can be worked with the same equipment or at the same time. The storage area can be irregular in shape.
4. Value of coal is increased because of less slacking.
5. Less storage space is required because of compaction.
6. Units can be added or subtracted without affecting continuity of operations.
7. Generally speaking, unit cost per ton handled is less.

The bulldozer and carryall requires only an initial pile to move the coal out to storage, and the reclaimed coal can be brought to a hopper connecting to the plant-conveying system. The method of stockpiling is briefly described as follows:

1. Clear area.
2. Spread coal in thin lifts, 4 to 8 in., over the entire area.

Table 18-19. Coal Storage and Reclamation Data<sup>1</sup>  
(Tonnage production and cost estimate for bulldozer and scraper)

One-way haul, ft	Tractor and dozer, draw bar hp						Tractor with scraper, draw bar hp							
	130		80		65		43		130 <sup>a</sup>		80 <sup>b</sup>		65 <sup>c</sup>	
	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr	Tons/hr	Cost, cents/hr
100	432	1.4	315	1.6	270	1.6	30	13.3						
150	315	1.9	224	2.3	192	2.3	22	18.2						
200	249	2.5	176	2.9	151	3.0	17	23.5						
250	206	3.1	146	3.5	125	3.6	14	28.5						
300	176	3.5	122	4.2	104	4.3	12	33.3	190	4.0	126	4.8	91	5.6
500									160	4.7	105	5.7	75	6.8
1,000									105	7.2	73	8.2	52	9.8
1,500									78	9.7	55	11	40	12.7
2,000									62	12.1	46	13	32	16
Data used for production and costs														
Machine cost/hr <sup>d</sup>	6.25		5.15		4.45		..		7.75		6.00		5.10	
Pay tons/load	8		7		6		..		12.6		7.7		5.6	
Dumping speed, mph	1.7		1.4		1.4		..				..		..	
Return speed, mph	3.7		5.4		5.4		..				..		..	
Travel and return speed, mph							..				..		..	
Fixed time, min	0.30		0.30		0.30		..		4.8		6.0		5.8	
Coal weight, lb/cu yd	1,400		1,400		1,400		1,400		2.5		2.5		2.5	
Efficiency, min/hr	60		60		60		60		1,400		1,400		1,400	
									60		60		60	

Note: Production figures reflect results of data typical of storage and reclamation conditions normally encountered. Any change in above conditions may tend to increase or decrease production.

<sup>1</sup> Caterpillar Tractor Co.

<sup>a</sup> 13.5 cu yd struck, 18 cu yd heaped.

<sup>b</sup> 8.7 cu yd struck, 11 cu yd heaped.

<sup>c</sup> 6 cu yd struck, 8 cu yd heaped.

<sup>d</sup> Machine cost per hour varies greatly. The above may or may not be representative of local conditions.

3. Spread second lift over the first, and return over the first lift to aid compactness. The vibration of the tracks, followed by the rolling kneading action of the large pneumatic tires on the scrapers, is responsible for this compaction.

4. Spread third lift and return over the second.

5. Spread fourth lift, etc.

6. Top off the storage pile by rounding edges and running tractor-dozzer back and forth to get additional compaction.

7. Seal the top with light bituminous mix for protection against rain and weather.

Recovery can be made with the same equipment. Because of compaction attained, a ripper may be necessary to break up coal for scraper loading. Some plants have built windbreakers on the wind side or all around storage piles to further fire protection.

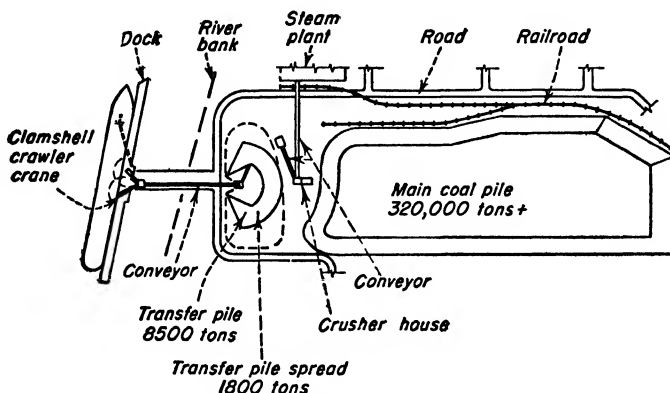


FIG. 18-48. Coal-handling installation and storage pile at the Polymer plant. (ASME No. 47-SA-12).

The compacting action of this type of equipment makes possible the stock-piling of bituminous coal to depths of 60 to 70 ft with minimum danger of coal overheating; heights up to 100 ft of coal depth have been utilized. The technique of coal handling with the bulldozer produces too much degradation of anthracite and coke for it to be recommended usually.

✓ **Tonnage Production and Cost Data.** Table 18-19 shows tonnage for various haul lengths along with cost per ton data in parentheses. The cost figures are useful only on a comparative basis, as costs vary widely in different sections. Changes in equipment price or in operator's wage scale would necessitate revisions. The following items are included to make up the *machine cost* per hour as shown in Table 18-19.

Fixed Cost	Variable Cost
Depreciation	Fuel oil, gasoline
Interest	Lubricating oil
Insurance	Grease
Taxes	Repairs, including labor
	Operator

Figure 18-48 illustrates the system used to handle coal at the Polymer plant, near Sarnia, Ontario. Self-unloading vessels dump the coal onto a conveying-belt system which deposits the coal on a transfer pile. The tractor carryall takes the coal to the storage pile. For reclaiming, the coal is taken by the tractor carryall to a sunken hopper. Belt conveyors bring the coal to the central station.

For further details on the bulldozer and carryall, consult Caterpillar Tractor Co., Peoria, Ill., and R. G. Le Tourneau Inc., Peoria, Ill.

SPONTANEOUS COMBUSTION<sup>1</sup>

Storage-pile heating is caused by the igniting of oxygen in the air with the coal. The rate at which oxygen unites with coal progressively increases with temperature.

Successful storage of coal requires either an unrestricted flow of air throughout the pile, which removes the heat of oxidation as rapidly as it is formed, or the practical absence of air flow within the pile, thus to limit the rate of oxidation.

The rate at which coal will absorb oxygen and generate heat is dependent upon:

1. The temperature at which the coal is stored
2. The size of the coal and distribution of sizes when placed in storage
3. Moisture conditions at the time of storage
4. The quantity and fineness of pyrites in the coal
5. The conditions of ventilation throughout the storage pile
6. The methods used in placing the coal in storage

The hazard of storing coal is dependent upon the combined effect of all these factors. One factor may favorably modify the normally adverse effect of another or, if both are adverse, the combined effect may be greater than the sum or product of the two if they could have been given numerical values.

**Effect of Temperature.** Coal starts to oxidize and burn slowly upon exposure to air. The rate of oxidation roughly doubles for each 15°F rise in temperature. Above 85°F, oxidation becomes appreciable, and 150°F represents the danger point for many coals. Low-rank coals, owing to high bed moisture and high oxygen content, tend to oxidize at a faster rate for any given temperature than high-rank coals having low bed moisture and oxygen content. This explains one of the reasons why Eastern coals tend to store better than Middle Western coals.

For these reasons, coal storage during extremely hot weather should be carried on only when adequate equipment is available so the various sizes may be mixed together and compacted in the pile, thus excluding air and preventing it from entering the pile.

**Effect of Segregation.** A coal pile heats because of oxidation and cools because of radiation and convection. When coal segregates as it is placed in the pile, ventilation becomes complicated and air currents are restricted in some sections and flow freely in others. The flues resulting from the coarse coal separating from the fines will allow considerable freedom of air movement, permitting that section to remain comparatively cool, while the fine-coal section, if somewhat damp, will pack so that little or no air will circulate and the coal will remain cool because of lack of air to oxidize the coal. Another section will contain flues of coarse and fine sizes which will restrict the movement of air, allowing sufficient air for oxidation but insufficient air to remove the heat of oxidation. This results in increased temperatures and a greater rate of oxidation, and eventually causes the pile to overheat.

**Effect of Moisture.** Experience of those who have stored large quantities of coal indicates that the storing of wet coal should be avoided if possible. The exact effect of moisture upon spontaneous combustion is not known, but the repeated wetting and drying of coal seems to increase the danger of heat, owing to (1) the effect moisture has upon compacting the fine sizes and its effect upon ventilation; (2) increasing the tendencies of weathering and slacking; and (3) increasing the heating activity of the pyrites because of chemical reaction.

**Effect of Sulphur.** Pyrite is a compound of iron and sulphur which unites with oxygen when wet and gives off heat in the process of forming iron sulphate and sulphuric acid. Investigations by the U.S. Bureau of Mines have shown that, when pyrites are finely divided, the danger of spontaneous heating is increased, owing to the increase in total surface area. If the coal is alternately wetted and dried, owing to

<sup>1</sup> Storage of Coal, *Ohio Coal Association Research Bull.*, Cleveland, Ohio, 1949.

segregation of sizes in the pile which permit seepage, the tendency for the pyrites to increase heating from chemical reaction is greatly augmented and eventually may cause trouble.

Careful storage methods will prevent segregation and thus exclude both air and moisture from the pile, permitting high-sulphur coals to be stored safely.

**Access of Air, Ventilation.** The greatest liability for spontaneous combustion occurs when sufficient air enters the pile to oxidize the coal, but insufficient to carry away the heat of oxidation as fast as it is generated. If ineffectual or no attempts are made to avoid segregation, the storage pile will be made up of a heterogeneous pattern of sizes which produce flues for the movement of air. Under these conditions, air will enter the pile in amounts depending upon wind velocity, the relation of ambient and internal-pile temperature, and chimney effect.

Since oxidation takes place on the coal surface, the smaller the size the greater the surface exposed and the more rapid will be the heating. The areas adjacent to the flues, caused by the coarse coal separating from the fines, are particularly vulnerable to overheating, and for this reason segregation must be avoided if the successful storage of coal is to be accomplished.

### Preventing Fires in Coal Storage Piles<sup>1</sup>

Coal can ignite and burn only in the presence of oxygen. To prevent ignition, it is necessary to keep oxygen from being supplied to the coal in a pile in sufficient quantities and at such a rate as to promote combustion. If air can penetrate a pile of coal, oxidation will occur at some rate which is a function of the temperature of the coal and the air. If the temperature rises as a result of this oxidation, the rate increases, and the rise in temperature is accelerated until fire occurs. If, however, the rate of supply of oxygen is so low that the dissipation of heat is equal to the heat generated, there will be no rise in temperature and the coal will not fire, although there may be some deterioration in the coal. This deterioration takes the form of a reduction of the heat value of the coal by an amount equal to the oxidation of the combustible matter.

The firing of coal in storage piles may be prevented by excluding the air. Coal should be laid down in uniform layers in such a manner that there is a minimum segregation of coarse and fines. It is desirable to pack each layer so that the greatest possible density is maintained throughout the pile. Thorough mixing of the coal sizes, together with packing, reduces voids through which air can pass. The edges of the pile should be sloped for drainage and sealed. Fines, well packed on the slopes, provide a very good seal against air infiltration.

### Storage-pile Fires with Anthracite

Probably because of its low volatile content combined with a relatively high ignition temperature, no authenticated case of spontaneous combustion has ever been reported in a storage pile of any size of anthracite.

Occasional fires have occurred in anthracite storage piles, but whenever they were expertly traced they were found to be due to one of the following causes:

1. A mixture of bituminous coal with the anthracite, either intentionally or through carelessness. The latter includes the handling of anthracite in trucks or other equipment improperly cleaned after handling bituminous, the mixing of screened yard fines with small anthracite where the former were collected indiscriminately and included bituminous screenings, and the placement of anthracite in a bin which still contains some bituminous coal.

<sup>1</sup> CRAIG, OLLISON, Meeting Wartime Fuel Problems, *Mech. Eng.*, vol. 64, No. 10, p. 697, October, 1942.

2. The contamination of the anthracite by materials subject to spontaneous combustion. This includes oily rags, trash, and other inflammable materials.

3. A source other than the coal but in the coal, such as a leaking oil or gas line. Sometimes a leaking steam line running through the coal will be erroneously reported as a fire.

Finn<sup>1</sup> calls attention to the fact that water can safely be used with such fires in an anthracite fire but not with bituminous coal.

### DUST-EXPLOSION HAZARDS<sup>2</sup>

As is shown in Table 18-20, virtually all hydrocarbons and carbohydrates, fertilizers, resins, waxes, and finely divided metals are capable of varying degrees and rates of ignition under the right circumstances.

The only exceptions, in several hundred materials included in the study, were anthracite dust and animal charcoal.

Actually, dust explosions have occurred in practically all kinds of grain-handling plants, such as grain elevators, flour and feed mills, and starch factories; and in many industries associated with the processing of agricultural products, such as sugar refining, the preparation of cocoa, chocolate, malt, powdered milk, and other food products, coal mines, wood pulp, wood products, soap powder, paper products, insecticides, fertilizers, and many others.

**Determination of Explosiveness.** A method that is easy and fairly reliable, but not infallible, is to pour the dust to be tested on a piece of cheesecloth about a yard square and, after gathering the ends to form a bag, shake dust through the cloth onto a burning match or other source of ignition. If the dust ignites, it is definite proof that it will explode when mixed with air in the proper proportions. Care must be taken to prevent burning the persons making the test. This method should not be used to test aluminum or magnesium powder.

### Dust Explosions During Firefighting

**Causes.** Some of the most serious dust explosions have occurred during firefighting. These may be classified as follows:

1. Explosions caused by the full stream of high-pressure water striking settled or static dust in various parts of the building. The water forces the dust cloud on the flames, and an explosion results.

2. Explosions that occur when firemen attempt to remove dust or powdered products from bins or other enclosures. When in the form of a cloud, these materials readily ignite upon coming in contact with the flames.

3. Explosions caused by falling floors or the dropping of the bottoms of storage bins, forcing the dust cloud on the fire and resulting in an explosion.

4. Explosions that result from the chemical reaction between water and dust. For example, a violent reaction takes place when water is applied to hot aluminum powder. Hydrogen is liberated and may form explosive mixtures with the air. The oxygen from the water also unites with the aluminum, resulting in rapid combustion.

**Mechanism of Dust Explosions.** A dust explosion consists essentially of pressure produced by the rapid burning of dust suspended in air. The pressure produced by the rapid burning of the dust cloud and the rate of pressure rise are responsible for the damage caused by the explosion. The rate of burning of the dust cloud is affected by the size, the ease of ignition, the heat of combustion of the dust particles, and the concentration of the dust in the air. At least 80 per cent of the pressure is due to the expansion of the gaseous products of combustion and the residual air brought about by the heat from the rapid combustion. In some cases the rest of the pressure is the

<sup>1</sup> FINN, E. E., consulting engineer, Anthracite Institute.

<sup>2</sup> Dust Explosions during Fire Fighting, *U.S. Dept. Agr. Circ.* 385, March, 1936.

**Table 18-20. Time-pressure Data for Various Dusts<sup>1</sup>**  
(Providing an indication of relative explosibility)

Material	Concentration, 100 mg/l <sup>2</sup>			Concentration, 500 mg/l <sup>2</sup>		
	Max pressure, psi	Avg rate of pressure rise, lb/sq in./sec	Max rate of pressure rise, lb/sq in./sec	Max pressure, psi	Avg rate of pressure rise, lb/sq in./sec	Max rate of pressure rise, lb/sq in./sec
<b>Carbon, coal, etc.</b>						
Wood charcoal.	23	165	266	42	146	294
Bituminous coal (Pittsburgh)	23	255	562	42	252	588
Coal-tar pitch	22	177	344	24	127	259
Coke	13	58	87	26	69	117
Lampblack	10	73	119	a	a	a
Carbon flour	4	28	28 <sup>b</sup>	3	23	23 <sup>b</sup>
Graphite	2	c	c	1	c	c
Anthracite	0	0	0	0	0	0
Animal charcoal	0	0	0	0	0	0
<b>Food products and by-products</b>						
Cellulose	27	284	814	46	414	1,111
Rice starch	26	233	546	41	218	852
Potato starch	18	138	361	38	257	722
Hard winter-wheat flour	21	127	363	40	219	614
Spring-wheat flour	20	121	330	34	177	567
Bran	4	23	23 <sup>b</sup>	30	121	288
Wheat-elevator dust	20	154	311	46	329	720
Cracker meal	20	108	272	41	240	481
Wheat smut (No. 1)	21	111	328	40	169	567
Cornstarch	23	166	577	43	360	863
Alkali starch	a	a	a	47	483	1,076
Corn-elevator dust	23	237	570	43	299	865
Yellow corn meal	13	77	121	36	165	411
Barley flour	19	119	242	35	271	739
Barley-elevator dust	14	76	175	37	127	404
Malt	22	177	403	36	179	541
Rye flour	20	132	465	36	295	722
Tapioca flour	20	210	529	42	278	715
Soybean flour	15	101	260	26	87	251
Peanut-hull flour	14	65	119	29	118	356
Oat dust from dry kiln	23	216	558	43	329	841
Oat hulls	12	62	132	35	121	254
Oat-elevator dust	20	135	383	38	139	601
Kafir corn	20	144	345	41	301	831
Alfalfa	16	93	172	32	117	289
Gelatin	28	214	470	a	a	a
Egg albumen	13	54	84	30	134	280
Linseed meal	12	65	141	25	99	216
Cottonseed meal	7	32	58	22	83	145
Cocoa	5	33	45	23	79	218
Powdered skim milk	26	209	465	41	210	423
Powdered buttermilk	20	118	226	42	176	320
Powdered milk	4	19	25	a	a	a
Powdered whole milk	17	91	219	31	142	441
Smoking tobacco	7	36	36 <sup>b</sup>	23	95	150
Tobacco-stem dust	1	c	c	1	c	c
<b>Wood, paper, tanning materials, etc.</b>						
Redwood	25	256	528	40	256	666
Redwood bark	22	201	413	38	250	557
White pine	23	146	603	44	156	459
California white pine	21	127	391	43	163	603
Longleaf yellow pine	22	177	467	43	196	516
Maple	23	177	522	37	142	516
Oak	22	155	461	40	162	552
Cedar	22	210	548	40	221	725
Spruce	21	164	456	39	145	456

Table 18-20. Time-pressure Data for Various Dusts.<sup>1</sup> (Continued)

Material	Concentration, 100 mg/l			Concentration, 500 mg/l		
	Max pressure, psi	Avg rate of pressure rise, lb/sq in./sec	Max rate of pressure rise, lb/sq in./sec	Max pressure, psi	Avg rate of pressure rise, lb/sq in./sec	Max rate of pressure rise, lb/sq in./sec
Fir . . . . .	18	117	265	37	149	365
Cork . . . . .	25	251	588	40	185	518
Black oak bark . . . . .	23	244	632	38	141	412
Chestnut wood . . . . .	27	242	856	40	203	578
Chestnut oak bark . . . . .	23	161	578	39	144	467
<b>Fertilizers</b>						
Soluble blood flour . . . . .	26	189	357	51	220	530
Raw bone . . . . .	21	182	431	39	230	503
Steamed bone . . . . .	2	17	17 <sup>b</sup>	3	27	27 <sup>b</sup>
Fish meal . . . . .	17	115	188	34	170	339
<b>Resins, waxes, soaps</b>						
Soap powder . . . . .	32	238	600	42	164	325
Sodium resinate . . . . .	31	185	430	36	166	357
Phenol aldehyde resin . . . . .	28	268	648	39	124	883
Shellac . . . . .	27	184	864	31	145	365
<b>Metals</b>						
Aluminum . . . . .	23	170	513	40	240	724
Magnesium . . . . .	23	140	469	49	270	788
Iron . . . . .	6	29	36	19	62	105
Zinc . . . . .	3	19	19 <sup>c</sup>	8	53	103
Gold bronze . . . . .	2	12	12 <sup>c</sup>	3	20	20 <sup>c</sup>
<b>Miscellaneous</b>						
Hard rubber . . . . .	23	265	593	37	248	504
Sulphur . . . . .	17	101	230	32	90	301
Lime-sulphur . . . . .	16	102	222	31	73	404

<sup>1</sup> EDWARDS, PAUL W., and I. R. LEINBACH, Explosibility of Agricultural and Other Dusts as Indicated by Maximum Pressure and Rates of Pressure Rise, *U.S. Dept. Agr. Tech. Bull.* 490, pp. 9-13, October, 1935

<sup>2</sup> The concentration as reported in mg per liter is equivalent to ounces of dust per 1,000 cu ft.

<sup>a</sup> Test made at one concentration only.

<sup>b</sup> Maximum rate of pressure rise was not determined. The value for average rate was inserted, as the maximum rate was equal to this at least.

<sup>c</sup> An indeterminable value.

result of an increase in the volume of the gases, the increase depending on the kind of dust that is burned. (This does not apply to explosives such as dynamite and smokeless powder, which do not depend upon oxygen in the air for combustion.)

In order to provide a rough relative gauge of the explosiveness of various dusts, the U.S. Department of Agriculture has tested and plotted the average rate of pressure rise, maximum rate of pressure rise, and maximum pressure for many commonly used products. Some of these are shown as Table 18-20. They point out that this is of necessity rather arbitrary, as many other field conditions might affect explosiveness; however, the tests are comparable and give a splendid indication of the relative hazards of the several dusts.

### Combating Dust Fires

The U.S. Department of Agriculture<sup>1</sup> offers the following general suggestions for fighting some of the more common dust fires:

**Grain Elevators.** A spray should be used on the fire instead of the full stream of the hose. Care should be exercised that the full stream at high pressure does not

<sup>1</sup> PRICE DAVID J., Dust Explosions during Fire Fighting, *U.S. Dept. Agr. Circ.* 385, 1936.



force settled dust on the burning fire. Men should be kept out of areas most likely to be affected should the dust explode.

**Wood-dust Storage Bins.** Considerable danger will be incurred if an attempt is made to remove the contents of the bin through the bottom. The sawdust will form an arch and ignite the cloud of dust when it breaks. The best procedure is to flood the bin by turning on the sprinklers and running the hose lines into the top of the bin. No attempt should be made to empty the bin until it is completely flooded and water starts to run out of the bottom.

**Feed Mills.** It is always desirable to fight such fires from the side rather than exposing firemen to danger by stationing them directly overhead. In this type of plant there is usually added danger from explosion due to the falling of the bottom of the bins. This should be carefully watched.

**Aluminum-powder Plants.** Great caution should be exercised in the use of water. Water should be kept off of the burning area and used exclusively for the protection of surrounding buildings. Small fires can be controlled by building a wall of dry sand around them to confine the fire until it burns out. Sand or similar material should never be thrown on such a fire.

## CHAPTER 19

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### HANDLING AND STORING LIQUID AND GASEOUS FUELS

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## FUEL-OIL HANDLING<sup>1</sup>

Oil is widely used to generate heat and steam in central stations, industrial plants, heating systems, locomotives, and steamships. In addition many large plants in the coal-burning areas are installing large oil storage and handling facilities to ensure fuel supplies during work stoppages in the coal-mining and rail industries. The handling and storage equipment are a large expenditure, but the preparation (heating and straining) equipment is a small item.

### Advantages, Storage and Handling.

1. Less storage space is required than with coal.
2. Fuel oil is not subject to spontaneous combustion.
3. Fuel oil is the most difficult to ignite of the liquid fuels.
4. Fuel oil is not subject to deterioration.
5. Fuel oil provides ease of storage, because of its fluidity, in normally inaccessible spaces such as ship double bottoms.
6. The fluidity of fuel oil makes for ease and rapidity of handling by relatively simple pump-heater-pipe system.
7. Fuel oil is free from dust nuisance and hazard.
8. Fuel oil is free from expensive manual handling.
9. Fuel-oil-handling system is less costly than equivalent coal-handling system.

### Disadvantages, Storage and Handling.

1. Vapors of fuel oil are inflammable and, when mixed with the proper amount of air, are explosive.
2. Storage tank and line leakage are losses. Accumulated vapors from leakage are dangerous.

**Typical Plant Layouts.** *Marine.* Delivery of fuel oil on board a vessel may be from an oil barge or from a shore station. The former is employed most frequently as delivery may be made while the vessel is discharging or taking on cargo. Flexible connections are made from the barge to the filling line on the ship. The oil pump on the barge is supplied with steam, either from a boiler on the barge or by a flexible steam line from the vessel being bunkered. This steam supply is also tapped for heating the oil prior to pumping.

The number and arrangement of **tanks** in a vessel is usually somewhat more complex than in a shore plant, as a result of the construction of the hull and the desire of the naval architect to utilize the available space efficiently, providing oil storage with minimum interference with cargo and machinery space. Fuel oil also offers a convenient means of maintaining the stability of the ship, as an oil storage tank after being drained may be filled with water for ballast. The fuel-filling system is preferably arranged with overflows so that while bunkering it is necessary to observe the level of the oil in only one or two tanks. Such an arrangement permits bunkering at maximum speed, with slight danger of loss from overflowing. The amount of oil in each tank is determined by direct soundings or by a gauge. A schematic drawing is shown in Fig. 19-1. The construction of the fuel-oil tanks should conform to the rules and regulations of the U.S. Department of Commerce, Bureau of Marine Inspection and Navigation.

As a part of the oil-tank system on board a vessel, it is customary to provide two deep tanks so located that the suction connections from them are above or nearly

<sup>1</sup> BARNARD, WILLIAM N., FRANK O. ELLENWOOD, and CLARENCE F. HIRSHFIELD, "Elements of Heat-power Engineering," 3rd ed., Part II, pp. 559-568, John Wiley & Sons, Inc., New York, 1923. SCHOENFELD, D. M., and G. P. HAYNES, Handling and Burning Fuels on Board American Ships, *Mech. Eng.*, March, 1947, pp. 161-167.

level with the fuel-oil service pumps. Each such tank is usually of adequate capacity to operate the vessel for 30 hr. These tanks are also known as **fuel-settling tanks**, and their purpose is to provide the means for settling out any water that may be entrained in the fuel oil. Most water remains in the double-bottom storage tanks as a result of incomplete drainage after being used as ballast tanks. These ballast tanks are filled with fuel oil from the double bottom or deep tanks by a fuel-oil transfer pump, usually utilizing the filling-system piping. The latter tanks are provided with

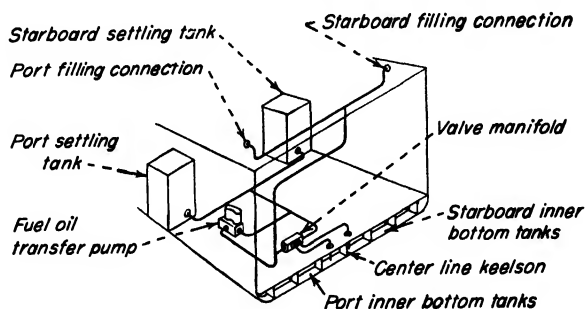


FIG. 19-1. Schematic arrangement of fuel-oil bunkers, deep tanks or oil settlers, etc. (*Mechanical Engineering.*)

steam-heating coils of sufficient area to reduce the viscosity of the oil to a degree where it is readily pumpable. The fuel-oil-settling tanks are provided with a series of steam grids which cause the water to precipitate by lowering the viscosity of the oil and helping to break emulsions. A period of 24 hr is allowed for this conditioning process, following which the water is stripped off and disposed. The condensate from the steam coils and grids is trapped and inspected for possible presence of oil due to leakage before it is returned to the boiler feed system.

From the fuel-oil-settling tanks the oil passes into the suction of the fuel-oil service pump, thence through the preheaters to the burners. Strainers at the suction and

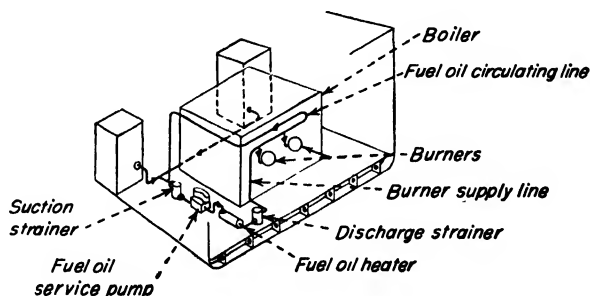


FIG. 19-1a. Schematic arrangement of fuel-oil service pumps, heaters, strainers, and burners. (*Mechanical Engineering.*)

the discharge of the fuel-oil service pump protect the pump and the burners from becoming fouled by any foreign substance present in the fuel oil (Fig. 19-1a).

**Stationary Systems.** The stationary system does not differ greatly from the marine system, except in the matter of the storage and settling tanks. Shown in Fig. 19-2 is schematic representation of a stationary system. Oil warmed by a coil heater is drawn from the storage tank through a suction strainer by a rotary pump. It is then sent through an oil heater and raised to the desired temperature for the required conditions at the burner. From the heater, it passes through a pressure strainer and

then to the burner. The strainers and the heaters are made in duplicate to facilitate maintenance while the system is in operation.

Where the storage tanks are located outside the building where the oil is utilized, the oil must be pumped from the tank through pipes to point of use. As these pipes are generally outdoors, they are subject to low-temperature conditions in the winter, making the oil difficult to pump. Provisions should be made to keep the connecting oil lines sufficiently warm so that service is not interrupted by low-temperature conditions.

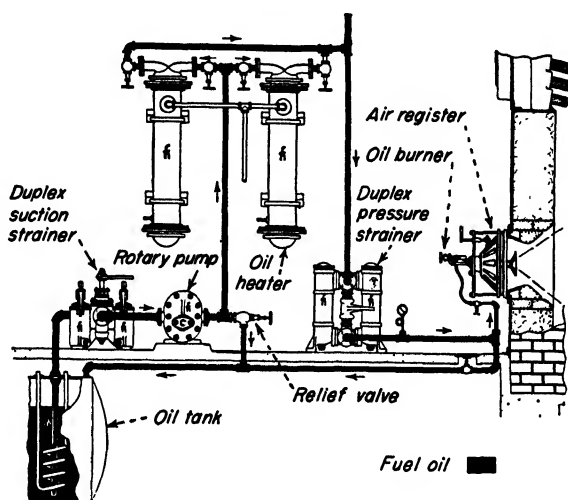


FIG. 19-2. Stationary oil-burner flow diagram. (Schulte & Koerting Co.)

**Storage tanks<sup>1</sup>** for oil should preferably be located outside of buildings and underground with the top of the tank below the level of all piping to which the tank is connected, to prevent discharge of oil through a broken pipe or connection by siphoning.

**Underground tanks** shall be so buried as to have a cover of earth not less than 2 ft thick, or shall be covered with not less than 1 ft of earth on top of which shall be placed a slab of reinforced concrete not less than 4 in. thick. The slab shall be set on a firm well-tamped earth foundation and shall extend at least 1 ft beyond the tank in all directions. Where tanks are buried underneath buildings, such a concrete slab shall be provided in every instance.

**Tanks inside Buildings.** Oil-supply tanks larger than 60 gal capacity shall not be located in buildings above the lowest story, cellar, or basement.

Unenclosed inside storage tanks and auxiliary tanks shall not be located within 7 ft, horizontally, of any fire or flame.

Oil-supply tanks located inside buildings shall not exceed 275 gal individual capacity or 550 gal aggregate capacity (in one building) unless installed in an approved brick or concrete enclosure or casing.

In buildings of ordinary construction, the nominal gross capacity of tanks shall not exceed 5,000 gal.

In fire-resistant buildings, the nominal gross capacity of the tanks shall not exceed 15,000 gal.

In any building, if in a fire-resistant or detached room cut off vertically and hori-

<sup>1</sup> *Natl. Board Fire Underwriters Pamphlet 31, New York, March, 1947.*

zonally, in an approved manner, from other floors of the main building, the nominal gross capacity of tanks shall not exceed 50,000 gal, with an individual tank capacity not exceeding 25,000 gal. See Table 19-1 for outside tank locations.

**Table 19-1. Outside Tank Location<sup>1</sup>**

Type of tank	All steel gastight of approved construction	Approved attached extinguishing system or approved floating roof	Liquid stored	Required distance between shell of tank and property line or nearest building	Max distance required
Group A	Yes	Equipped with either	Refined petroleum products or other flammable liquids not subject to boil-over	1 times greatest dimension—diameter, length, or height	Need not exceed 120 feet
Group B	Yes	Not equipped with either	Refined petroleum products or other flammable liquids not subject to boil-over	1½ times greatest dimension—diameter, length, or height	Need not exceed 175 feet
Group C	Yes	Equipped with either	Crude petroleum or other flammable liquid subject to boil-over	2 times greatest dimension—diameter, length, or height	Need not exceed 175 ft and not less than 20 ft
Group D	Yes	Not equipped with either	Crude petroleum or other flammable liquid subject to boil-over	3 times greatest dimension—diameter, length, or height	Not less than 20 ft and need not exceed 350 ft

NOTE: The minimum distance between shells of any two all-steel gastight tanks shall not be less than ½ the greatest dimension—diameter, length, or height—of smaller tank, except that such distance shall not be less than 3 ft, and for tanks of 18,000 gal or less, the distance need not exceed 3 ft. Tanks shall be so located as to avoid possible danger from high water. When tanks are located on a stream without tide, they shall, where possible, be downstream from burnable property.

<sup>1</sup> *Natl. Board Fire Underwriters Pamphlet 31, New York, March, 1947.*

**Embankments or Dikes.** In locations where aboveground tanks are liable, in case of breakage or overflow, to endanger surrounding property, each tank shall be protected by an embankment or dike of approved construction. Such dikes shall have a capacity of not less than that of the tank or tanks surrounded. Small tanks with capacities of not over 25,000 gal each may be grouped and a dike built around the group of tanks.

**Construction of Tanks.** Underground tanks and tanks inside buildings shall be constructed of steel or wrought iron of a minimum gauge (U.S. Standard) in accordance with Table 19-2, except that, for tanks of 181 to 275 gal capacity, installed in buildings, and without masonry enclosures, the minimum gauge shall be No. 14 steel, or wrought iron thinner than No. 7 gauge used in the construction of underground and enclosed tanks shall be galvanized.

**Outside aboveground tanks,** including tops, shall be constructed of steel or wrought iron of a thickness in accordance with the requirements in Table 19-3, and the following.

**Table 19-2. Storage-tank Shell Thickness**

Capacity, gal	Min thickness	Weight, lb/sq ft
7– 285	16 gauge	2 50
286– 560	14 gauge	3 125
561– 1,100	12 gauge	4 375
1,101– 4,000	7 gauge	7 50
4,001–12,000	¾ in. (nominal)	10 00
12,001–20,000	⅝ in. (nominal)	12 50
20,001–30,000	⅞ in. (nominal)	15 00

NOTE: If adequate internal bracing is provided, tanks of 12,001 to 30,000 gal capacity may be built of ¾ plate. For tanks larger than 1,100 gal capacity, a tolerance of 10 per cent in capacity is permitted.

**Table 19-3. Horizontal or Vertical Tanks Not over 1,100 Gal Capacity**

Capacity, Gal	Min Thickness of Material, U.S. Standard Gauge
1- 60	18
61- 350	16
351- 560	14
561-1,100	12

**Horizontal Tanks over 1,100 Gal Capacity.** Tanks having a diameter of not over 6 ft shall be made of at least  $\frac{3}{16}$ -in. steel or wrought iron.

Tanks having a diameter of over 6 ft and less than 11½ ft shall be of at least  $\frac{1}{4}$ -in. steel or wrought iron.

**Vertical Tanks over 1,100 Gal Capacity.** The minimum thickness of shell or bottom shall be  $\frac{3}{16}$  in. The minimum thickness of roof shall be  $\frac{1}{8}$  in.

The thickness of shell plates shall be in accordance with the following formula:

$$t = \frac{H \times D}{8,450 \times E}$$

where  $t$  = thickness of plate, in.

$H$  = height of tank, ft above bottom of ring under consideration

$D$  = diameter of tank, ft

$E$  = efficiency of vertical joint in ring under consideration

In computing the efficiency of vertical joints, the tensile strength of steel shall be taken as 55,000 psi and the shearing strength of rivets as 40,000 psi.

**Protective Coating.** Prior to installation, underground and enclosed tanks shall be protected against corrosion on the outside in a manner satisfactory to the inspection department having jurisdiction, but in every case at least equivalent to two preliminary coatings of red lead followed by a heavy coating of hot asphalt.

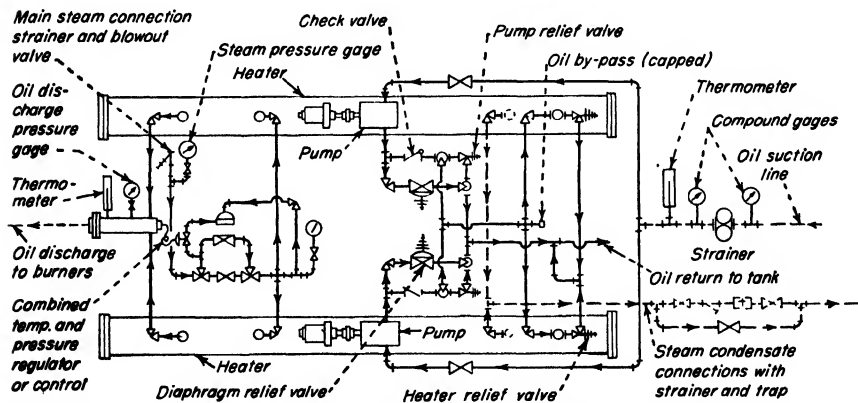


FIG. 19-3. Pump and heater set. Diagrammatic representation of the piping and controls and the flow of oil and steam. (The Engineer Company.)

**Vents.** Storage tanks shall (except for hydraulic or inert-gas systems) be equipped with an open vent or an approved automatic vent operated to discharge to the open air. Vent openings and vent pipes shall be of ample size to prevent abnormal pressure during filling, but not smaller than 1¼-in. pipe size. Vents shall be installed in an approved manner.

**Delivery.** Where the plant is supplied by tank car on a railroad spur to the plant, many systems have an auxiliary tank of about 15,000 gal (slightly more than the volume of the normal tank car) close to the transfer-pump house. The transfer pump is used to pump the oil through a strainer from the auxiliary to the main storage tank.

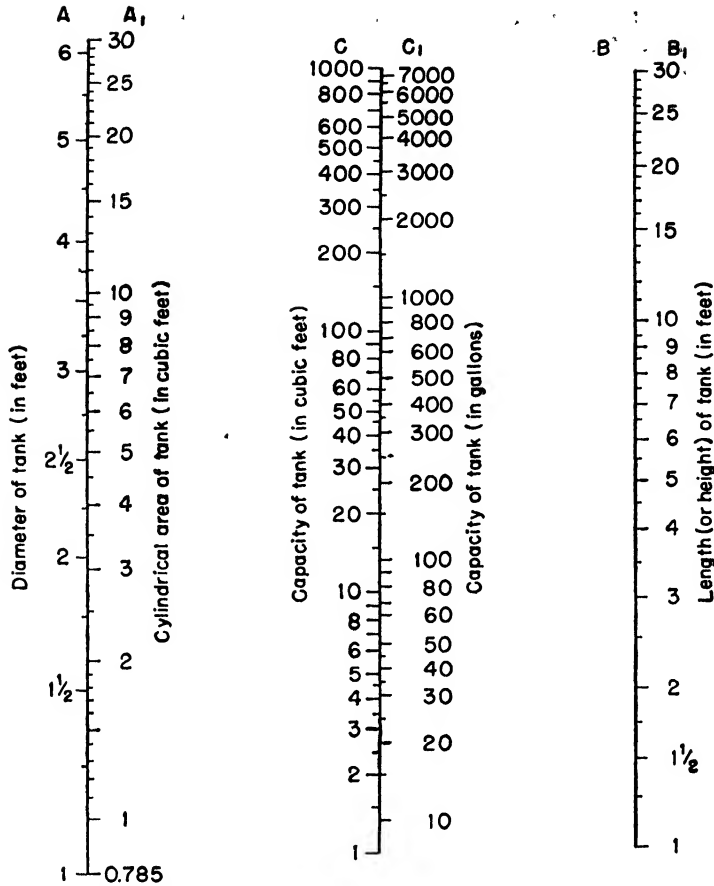


FIG. 19-4. Capacity of cylindrical tanks in cubic feet and gallons.

Table 19-4. Enco Fuel-oil Pumping and Heating Systems<sup>1</sup>

Size No.	Capacity			Pump size, in.	Pipe sizes, in.				Weight, lb	For heating lb steam/hr	For pumping lb steam/hr
	Gpm	Gph	Hp		Oil		Steam				
					In-let	Dis-charge	In-let	Exit			
0	3	180	500	3 × 2 × 3	1½	1	¾	¾	1,200	73	85
1	5	300	1,000	3½ × 2½ × 4	1½	1	¾	¾	2,000	122	109
2	7½	450	1,500	4½ × 2¾ × 4	2	1½	¾	1	3,000	182	163
3	10	600	2,000	5¼ × 3½ × 5	2½	1½	1	1¼	3,500	244	218
4	15	900	3,000	5¼ × 3½ × 5	2½	1½	1	1¼	4,000	365	327
5	20-25	1,500	5,000	6 × 4 × 6	3	2	1¼	1½	5,000	609	545
6	25-35	2,100	7,000	7½ × 5 × 6	4	2½	1½	2	8,000	852	763
7	35-50	3,000	9,000	7½ × 5 × 10	4	3	1½	2	9,000	1,218	1,090

<sup>1</sup> The Engineer Co.



**Fuel-oil Pumps.** There are four main types of pumps commonly used in fuel-burning systems. They are the double screw, the gear pump, the vane or rotary, and the reciprocating.

**Pump and Heater Sets.** To handle the fuel oil from storage tank to the burner, there is frequently installed a duplex unit consisting of an assembly of strainers, pumps, heaters, regulators, thermometers, pressure gauges, and any other control or instrument that is required. A diagrammatic sketch of such a unit is shown in Fig. 19-3.

#### Oil-fire Control

The usual types of oil-fire-extinguishing equipment rely on smothering the flame by reducing the supply of oxygen so that combustion cannot be maintained. In

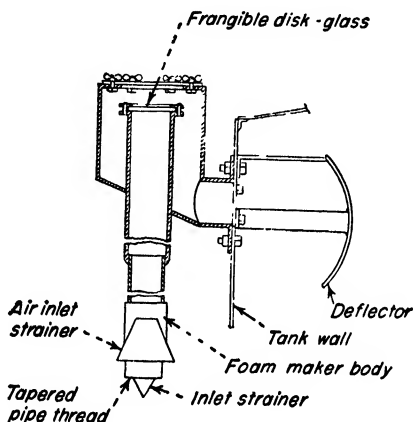


FIG. 19-5. Type C foam chamber. Frangible disk prevents leakage. This disk is sealed in position, and when foam pressure is applied it is ruptured, permitting the foam to enter the tank. (National Foam System, Inc.)

Type	Capacity, gpm, foam-maker pressure				Solution pipe sizes, normal run, in.
	50 lb/in. <sup>2</sup>		100 lb/in. <sup>2</sup>		
	Water	Foam	Water	Foam	
C-6	42½	425	60	600	2
C-12	85	850	120	1,200	2½
C-24	170	1,700	240	2,400	3
C-36	225	2,550	360	3,600	4

general these are of two types, a tenacious foam and an inert gas such as carbon dioxide.

**Foam System.** Effective foam is that having high cohesive and adhesive properties. Good foam must flow freely enough to cover a tank surface rapidly and be heavy enough to provide a gastight blanket. Light frothy foam breaks down quickly under high temperatures and is more easily carried away by drafts. The stabilizing agent used in compounding foam chemicals is of utmost importance, as it is upon this that the quality of the foam bubbles depends.

Either fresh water or sea water may be used to produce foam by the dry-powder-generator method. The temperature of the water may be that of the common sources of supply.

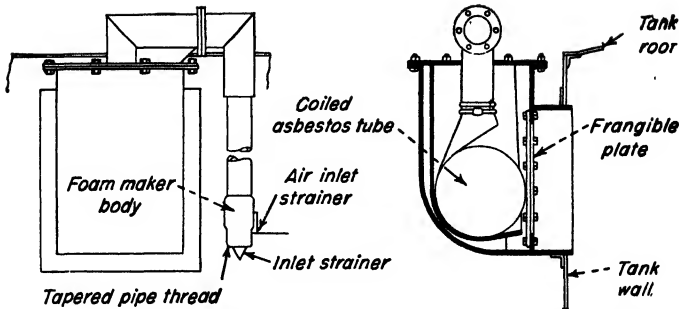


FIG. 19-6. Type L foam chamber. This type affords about 50 per cent saving in liquid requirements over type C of Fig. 19-5. When foam pressure is applied, the coarsely woven asbestos tube, coiled in the chamber, is expelled and as it floats on the surface of the liquid the foam exudes from the openings in the mesh. Splashing is avoided and the foam is greatly conserved. An absolutely gastight installation is provided by the frangible plate. (National Foam System, Inc.)

Type	Capacity, gpm, foam-maker pressure				Size Moeller-Foman asbestos tube	Solution pipe sizes, normal run, in.
	50 lb/in. <sup>2</sup>		100 lb/in. <sup>2</sup>			
	Water	Foam	Water	Foam		
L-12	85	850	120	1,200	7 in. × 40 ft	2½
L-24	170	1,700	240	2,400	10 in. × 50 ft	3
L-36	225	2,550	360	3,600	10 in. × 50 ft	4

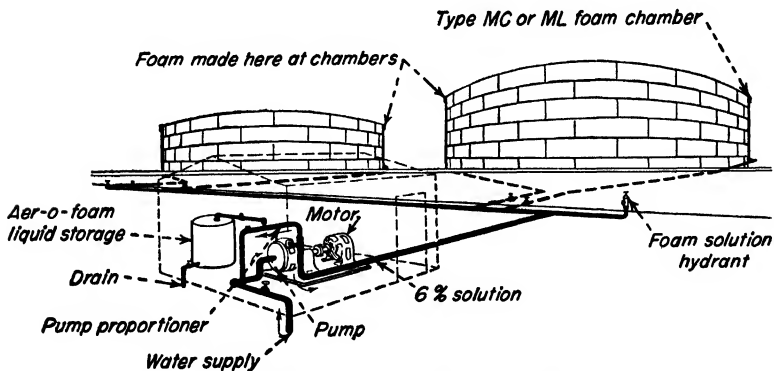


FIG. 19-7. Protection of oil-storage tanks by stationary foam system. The 6 per cent solution of foam and water, proportioned at the pump, is fed to the foam generators where the requisite air is added to make the foam. (National Foam System, Inc., Philadelphia, Pa.)

The most effective means of introducing foam to a tank is through the medium of a foam chamber (see Figs. 19-5 and 19-6) designed to remain in position in case of an explosion and also to provide a suitable rupturable diaphragm to prevent the condensation vapors in the foam-solution lines. It is the consensus among users of foam equipment that "roof-type" chambers are obsolete.

In the absence of foam chambers, foam may be applied through portable foam

towers or by means of hose streams. For spills or dike fires, hose streams are frequently the only means of protecting adjoining property. With the modern devices producing as high as 4,500 gpm, foam may be thrown by hose streams in excess of 150 ft. Foam hydrants (Fig. 19-7) are therefore an important accessory for both single- and dual-line layouts.

**Table 19-5. Foam Quantities for Various Tank Diameters and Liquid Fuels<sup>1</sup>**  
(Foam chemicals in pounds, when type L chambers are used)

Tank diam, ft	Tank area, sq ft	Gasoline, benzol, etc.	Kerosene, light furnace oils, etc.	Lubricating oils, residuum, etc.	All crude petroleum
15	177	600	500	400	700
18	254	900	700	500	1,000
25	491	1,600	1,300	1,000	2,000
30	707	2,400	1,900	1,400	2,800
36	1,018	3,400	2,700	2,100	4,100
48	1,810	6,000	4,800	3,600	7,200
60	2,827	9,500	7,600	5,800	11,500
70	3,849	13,000	10,200	7,800	15,400
78	4,778	16,000	12,800	9,500	19,000
90	6,362	21,200	17,000	12,800	25,400
102	8,171	27,300	21,800	16,500	33,000
115	10,387	34,500	27,600	20,800	41,500
120	11,310	37,800	30,200	22,500	45,000
144	16,286	54,000	43,200	32,500	65,000

<sup>1</sup> National Foam System, Inc., Philadelphia, Pa.

**Table 19-6. Foam Quantities for Various Tank Diameters and Liquid Fuels**  
(Foam chemicals in pounds, when type C chambers are used)

Tank diam, ft	Tank area, sq ft	Gasoline, benzol, etc.	Kerosene, light furnace oils, etc.	Lubricating oils, residuum, etc.	All crude petroleum
15	177	1,200	700	600	1,200
18	254	1,700	1,000	900	1,700
25	491	3,300	2,000	1,600	3,300
30	707	4,700	2,800	2,400	4,700
36	1,018	6,800	4,100	3,400	6,800
48	1,810	12,000	7,200	6,000	12,000
60	2,827	19,000	11,500	9,500	19,000
70	3,849	26,000	15,400	13,000	26,000
78	4,778	32,000	19,000	16,000	32,000
90	6,362	42,500	25,400	21,200	42,500
102	8,171	54,500	33,000	27,300	54,500
115	10,387	69,000	41,500	34,500	69,000
120	11,310	75,500	45,000	37,800	75,500
144	16,286	108,000	65,000	54,000	108,000

<sup>1</sup> National Foam System, Inc., Philadelphia, Pa.

The manner in which foam is applied to burning fluid surfaces has a direct bearing upon the amount of available chemicals required (Tables 19-5 and 19-6).

Experience has shown that fighting large fires with foam is most effectively accomplished when a large volume is delivered in a short space of time. Units of large capacity not only provide greater protection but actually use less chemicals per

square foot of surface involved. The loss of foam through flame and draft at times reaches a point where units of small capacity are ineffective.

**Carbon Dioxide.**<sup>1</sup> This type of fire-extinguishing system is effective primarily because it reduces the oxygen content of the air to a point where it will no longer support combustion. Under suitable conditions of control and application, a cooling effect is also realized.

A reduction of the oxygen content from the normal 21 to 15 per cent will extinguish most fires in spaces which do not include materials that produce glowing embers or smoldering fire.

Carbon dioxide is an inert gas, heavier than air. It is stored under pressure (800 to 900 psi at room temperature) as a liquid. In general, 1 lb of liquid carbon dioxide will produce about 8 cu ft of gas at atmospheric pressure. For fixed installations,

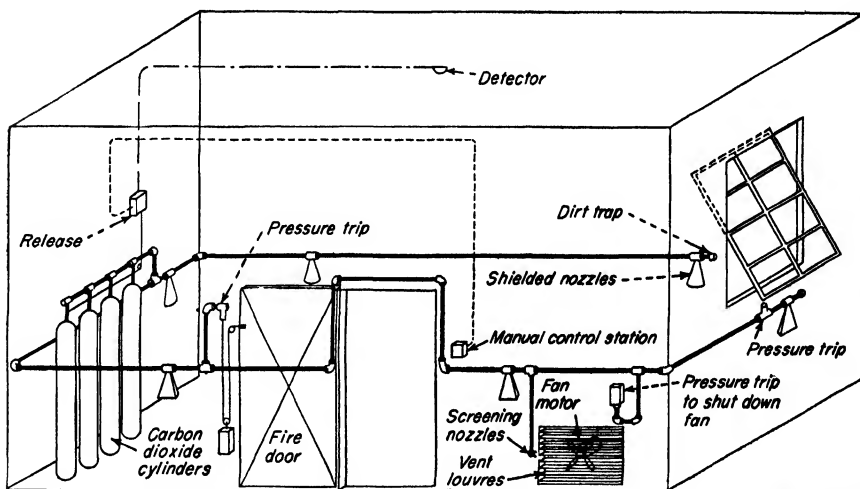


FIG. 19-8. Diagrammatic layout of typical total-flooding installation. (Walter Kidde & Co.)

cylinders containing 50 or 75 lb of  $\text{CO}_2$  are usually used. Portable installations may be of either smaller or larger weight.

A total-flooding installation is shown in Fig. 19-8. An absolutely tight enclosure is not necessary. Where possible, all openings such as doors and windows should be provided with automatic-closing devices. Where this is not practical, the openings should be provided by screening the outlet with discharge nozzles. The supply of gas should not be less than shown in the following table:

Where openings are screened by nozzles, larger quantities of gas are required. If a smoldering fire can be deep-seated, it may be necessary to use quantities of carbon dioxide as large as 1 lb per 6 cu ft of volume to be flooded.

Gas, Cu Ft/Lb	Space Protected, Cu Ft
16	Up to 1,600
18	Up to 4,500
20	Up to 50,000
22	Over 50,000

Oil-storage tanks having a surface area of over 250 sq ft are not usually protected by carbon dioxide, although it has been used effectively to extinguish fires at vents and other openings in the tops of large oil tanks.

**Occurrence of Fires.** Table 19-7 was compiled by the National Fire Protection Association, Department of Fire Record, Boston, Mass. These figures represent an

<sup>1</sup> CROSBY, FISKE, and FORSTER, "NFPA Handbook of Fire Prevention," 10th ed., pp. 1109-1117, National Fire Protection Association, Boston, 1948.

analysis of typical fires in their files and are by no means a complete record. They

**Table 19-7. Oil Tank, Farms Basis, 209 Fires<sup>1</sup>**

Broad Breakdown	Per Cent
Special hazards . . . . .	45
Common hazards . . . . .	41
Unknown causes . . . . .	14
Total . . . . .	100
<i>Special Hazards</i>	
Tank fire or explosion . . . . .	47
While cleaning . . . . .	18 0
Spillage while loading . . . . .	7.5
Static spark while loading . . . . .	6 5
While riveting or repairing . . . . .	5 6
Unknown cause . . . . .	5 6
Material failure . . . . .	3 2
Miscellaneous . . . . .	0.6
Tank-truck filling . . . . .	17
Valve or pipe failure . . . . .	16
Pumping . . . . .	11
Miscellaneous . . . . .	9
Total . . . . .	100
<i>Common Hazards</i>	
Lightning . . . . .	82
Exposure . . . . .	12
Grass or similar fire . . . . .	4
Incendary . . . . .	2
Total . . . . .	100

<sup>1</sup> National Fire Protection Association. Compiled Aug. 8, 1948.

Gas handling can be summarized as follows:

1. Piping
2. Booster or pressure reducer
3. Safety valve for line-pressure drop
4. Valves
5. Flowmeter

#### **Advantages—Storage and Handling of Gas.**

1. Usually no storage space is required as the utility is responsible for delivery. Some large gas consumers will have storage tanks. In the case of liquefied petroleum gas, storage space is required.

2. Fuel is not subjected to spontaneous combustion or deterioration, as is coal.

3. Gas provides the simplest handling problem of any of the fuels, as only piping is required along with safety and control equipment.

4. Gas is free from dust nuisance and hazard.

5. Gas-handling system is the least costly of all the fuels.

**Disadvantages—Storage and Handling of Gas.** Escaped gases are a serious menace, as they are explosive when mixed with the proper amount of air.

#### **Piping**

The calculation of flow in gas pipes is complicated by pipe-flow obstruction of roughness, tar, water, and other foreign material, tending to retard the flow of gas through the pipe. A well-known formula<sup>1</sup> for the flow of gas in pipes under low pressure is as follows:

$$Q = c \frac{d^5(p_1 - p_2)}{sL}$$

<sup>1</sup> Computer, copyrighted, *Am. Gas J.*, New York, 1935.

#### **GAS HANDLING**

Of all the fuels available, gas has the least complicated handling problem and from that point of view is the least expensive to install. In general, the supply line and the meter are the problem of the utility company supplying the gas, and the handling equipment from the meter is the responsibility of the consumer. The utility should always be consulted as to the details of the engineering and construction, and their recommendations should be followed. The following references list gas engineering and appliance manufacturers: Brown's Directory of American Gas Co. and Index of Prominent Manufacturers, Moore Publishing Co., New York; and Gas Engineering and Appliance Directory, *Gas Age*, Robbins Publishing Co., Philadelphia, Pa.

where  $Q$  = flow, cu ft/hr

$d$  = internal diameter of pipe, in.

$p_1$  = initial pressure, in. water

$p_2$  = final pressure, in. water

$s$  = specific gravity of gas (air = 1)

$L$  = length of pipe, yd

$c$  = a constant given as 1,000 by Molesworth and as 1,350 by Pole

Table 19-8. Pressure Drop by Friction of Air<sup>a</sup> in Pipes<sup>1</sup>

Velocity, fpm	Diam of pipes, in.									
	1	2	3	4	6	8	10	12	16	18
Pressure, oz/sq in. lost by friction of air in pipes 100 ft long										
100	0 011	0 006	0 004	0 003	0 002	0 001	0 001	0 001	0 001	0 001
200	0 044	0 022	0 015	0 011	0 007	0 006	0 004	0 004	0 003	0 002
300	0 100	0 050	0 033	0 025	0 017	0 012	0 010	0 008	0 006	0 006
400	0 178	0 088	0 059	0 044	0 030	0 022	0 018	0 015	0 011	0 010
500	0 278	0 139	0 092	0 069	0 046	0 035	0 028	0 023	0 017	0 016
600	0 400	0 200	0 133	0 100	0 067	0 050	0 040	0 033	0 025	0 022
700	0 544	0 272	0 181	0 139	0 091	0 068	0 054	0 045	0 034	0 030
800	0 711	0 356	0 237	0 178	0 119	0 089	0 071	0 059	0 044	0 040
900	0 900	0 450	0 300	0 225	0 150	0 112	0 090	0 075	0 056	0 050
1,000	1 111	0 556	0 370	0 278	0 185	0 139	0 111	0 92	0 069	0 062
1,100	1 344	0 672	0 448	0 338	0 224	0 168	0 134	0 112	0 084	0 073
1,200	1 600	0 800	0 553	0 400	0 267	0 200	0 160	0 133	0 100	0 089
1,300	1 878	0 939	0 626	0 469	0 313	0 235	0 188	0 156	0 117	0 104
1,400	2 178	1 089	0 726	0 544	0 363	0 282	0 218	0 181	0 136	0 121
1,500	2 500	1 250	0 833	0 625	0 417	0 312	0 250	0 208	0 156	0 139
1,600	2 844	1 422	0 948	0 711	0 474	0 356	0 284	0 237	0 178	0 158
1,700	3 211	1 605	1 070	0 803	0 535	0 401	0 321	0 268	0 207	0 178
1,800	3 600	1 800	1 200	0 900	0 600	0 450	0 360	0 300	0 225	0 200
1,900	4 011	2 006	1 337	1 003	0 669	0 501	0 401	0 334	0 251	0 223
2,000	4 444	2 222	1 481	1 111	0 741	0 556	0 444	0 370	0 278	0 247
2,200	5 378	2 689	1 793	1 344	0 896	0 672	0 538	0 448	0 336	0 299
2,400	6 400	3 200	2 133	1 600	1 067	0 800	0 640	0 533	0 400	0 356
2,600	7 511	3 756	2 504	1 877	1 252	0 939	0 751	0 626	0 468	0 417
2,800	8 711	4 356	2 904	2 178	1 452	1 089	0 871	0 726	0 544	0 484
3,000	10 000	5 000	3 333	2 500	1 667	1 250	1 000	0 833	0 625	0 566
3,200	11 378	5 689	3 792	2 844	1 896	1 422	1 138	0 948	0 711	0 632
3,400	12 844	6 422	4 281	3 211	2 141	1 606	1 284	1 070	0 827	0 714
3,600	14 400	7 200	4 800	3 600	2 400	1 800	1 440	1 200	0 900	0 800
3,800	16 044	8 022	5 349	4 011	2 674	2 006	1 604	1 337	1 003	0 891
4,000	17 778	8 889	5 926	4 444	2 963	2 222	1 778	1 481	1 111	0 988
4,200		9 800	6 553	4 900	3 267	2 450	1 960	1 633	1 225	1 089
4,400		10 705	7 175	5 353	3 569	2 676	2 141	1 784	1 344	1 189
4,800		12 800	8 533	6 400	4 267	3 200	2 560	2 133	1 600	1 422
5,200		15 022	10 015	7 511	5 007	3 756	3 004	2 504	1 871	1 670
5,600		17 422	11 615	8 711	5 807	4 356	3 484	2 904	2 178	1 936
6,000		20 000	13 333	10 000	6 667	5 000	4 000	3 333	2 500	2 222

<sup>1</sup> Hauck Industrial Combustion Data, p 97, prepared by Spencer Turbine Co.

<sup>a</sup> For other gases, the pressure drop varies directly as the square root of the specific gravity. Thus, for a gas (specific gravity = 0.5) with a velocity of 500 fpm in a 4-in. pipe, the pressure drop would be  $0.069 \times \sqrt{0.5} = 0.048$  per 100-ft length of pipe. For other pipe lengths, the pressure drop is directly proportional.

With reasonably clean pipe and under the usual conditions, the use of the following constants is suggested:

Internal diam, in.....	$\frac{3}{4}$ -1	1 $\frac{1}{2}$	2	3	4 and larger
Constant	1,000	1,100	1,200	1,300	1,350

Problems involving the sizing of gas pipe using this equation can be readily solved by the use of a computer made up of circular sliding scales. This can be purchased reasonably from the *American Gas Journal*.

An equation taken from "Gaseous Fuels"<sup>1</sup> for low-pressure flows, in which the change in density of the gas is not important and in which the flow is turbulent, is as follows:

$$Q = \frac{2331 h^{0.543} d^{2.631}}{S^{0.468} L^{0.543}}$$

where  $Q$  = cu ft/hr

$d$  = diameter of pipe, in.

$S$  = specific gravity of the gas at the temperature and pressure in question relative to air at room temperature and 30 in. Hg

$h$  = pressure drop, in. water

$L$  = length of pipe, ft

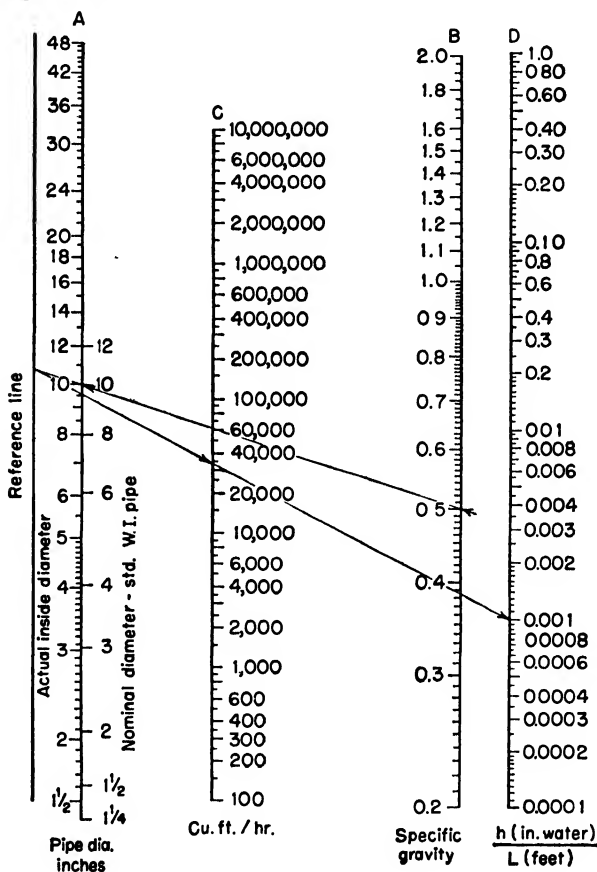


FIG. 19-9. Flow of gas in commercial pipes. Valid only for turbulent flow at low pressures and for low percentage pressure drops. Note that specific gravity of gas is for actual temperature and pressure conditions in the pipe, referred to air at 30 in. of mercury and room temperature. To use as in example, connect 10-in. pipe of A to 0.5 specific gravity of B to locate point on reference line. From point on reference line connect to  $h/L$  ratio of D to give the flow of 33,000 cu ft/hr of C.

<sup>1</sup> SCHNIDMAN, L., Editor, "Gaseous Fuels," pp. 65, 66, AGA, New York, 1948.

A nomograph for the convenient graphical solution of the above equation is given in Fig. 19-9.

Valves, elbows, tees, etc., add resistance to gas flow which can be expressed in terms equivalent to added feet of pipe. Table 19-9 presents practical data relative to the length in feet of standard pipe to allow for fittings.

**Table 19-9. Equivalent Length in Feet of Standard Pipe for Various Screw Fittings<sup>1</sup>**

Pipe size, in.	Elbow			Valve			Close return bend	Tee through side outlet
	Standard	Medium sweep	Long sweep	Gate	Globe	Angle		
$\frac{1}{8}$	0 84	0 52	0 41	0 031	2 50	1.12	1 25	1 66
$\frac{3}{8}$	1 17	0 73	0 57	0 044	3 50	1 87	1 75	2 33
1	1 57	0 98	0 77	0 057	4 68	2 11	2 34	3 11
$1\frac{1}{4}$	2 19	1 37	1 07	0 082	6 54	2 94	3 27	4 35
$1\frac{1}{2}$	2 63	1 64	1 29	0 098	7 84	3 52	3 92	5 21
2	3 55	2 23	1 74	1 320	10 60	4 77	5 30	7 05
3	5 72	3 59	2 81	2 130	17 08	7.69	8.84	11 40

<sup>1</sup> "Gaseous Fuels," AGA.

### Incidental Equipment

A gas booster is used where the gas pressure is too low, and a pressure-reducing valve is used where the gas pressure is too high.

**Boosters.** A typical radial-vane or paddle-wheel type of gas booster consists of a standard pressure blower equipped with a gastight seal around the shaft. The inlet and outlet are fitted with gastight connections. The function of the gas booster is simply to add its rated pressure to the existing line pressure. Where the high pressure is required for peak-load demands, the booster is kept in operation. When the load peak recedes and the existing line pressure is sufficient, the booster is shut down. The line pressure then forces the gas through the idle booster.

One of the applications of the gas booster is to plants that have added appliances to such an extent that the existing piping is insufficient in size. The use of the booster eliminates the necessity of repiping, provided that the supply gas main is of ample capacity.

The gas booster is made in a wide variety of sizes, from  $\frac{1}{8}$  to 30 hp, from 4,000 to 200,000 cu ft per hr, and for pressure increases of 2 to 30 in. water.

**Pressure Reducers.** Where the gas pressure is too high, a pressure-reducing valve is used. This same valve is also used to supply constant pressure to the appliance. Despite variations of the supply pressure (as long as the inlet pressure is above the desired outlet pressure), the desired outlet pressure is maintained at that specified. The spring-loaded type has an outlet pressure variation of 25 per cent above or below pressure specified. There is also available a dead-weight regulator which is used for the lower supply pressures. In this type, the outlet pressure is fixed and cannot be varied.

**Valves.** The function of the valve in the gas-handling system is to control or shut off the gas supply. These can be divided into two groups, manual and automatic.

**Manual Valves.** The common types of valves as applied to gas handling are the gate, the globe, and the one-fourth turncock.

**Automatic Valves.** The automatic valve is essentially a controlling device. It can be tied in with a safety valve, some temperature-sensitive mechanism, or some form of limit control. There are three general types of automatic valves, the solenoid, the motorized, and the diaphragm. The comparison of these types is given in Table 19-10.



•  
Table 19-10. Comparison of Automatic Valves

Type of valve	Seating	Action	Application
Solenoid.	Less positive	Rapid, gives surges	Better for ON-OFF control than for throttling
Motorized . . .	More positive	Slower action	Better for throttling, step control (high-low control) used for ON-OFF
Diaphragm . . . .	More positive	Slower action	Better for throttling (high-low control). Used for ON-OFF

**Safety Valve.** In order to eliminate the possible hazards due to line-pressure failure, some form of automatic safety should be installed. When the supply pressure drops below a predetermined value, the supply line is closed and locked. Without such a safety, when the supply pressure drops, the flame may go out unbeknownst to the operator. If the gas pressure should rise, the gas would be discharged through the unlit burner and be a potential explosive hazard.

**Flowmeters.** Unless a gas meter is timed it cannot give an indication of the flow of a gas. Also, timing a gas meter gives only an average flow for the timing period. Some form of flowmeter is useful to the operator, since it gives a quick indication of the rate of gas consumption. In many installations, two flowmeters are set side by side, one for the gas and one for the air, so that air and gas may be accurately proportioned.

#### Underground Storage of Natural Gas

In addition to the familiar low- and medium-pressure types of gas storage, such as the gasometer, two additional methods have recently been developed.

1. The forcing of gas received from transmission lines back into nearby oil or gas wells under high pressure. The gas, thus available for use when needed, relieves peak loads on the long-distance pipe lines.

2. The storage of gas in underground pipes. According to *Compressed Air Magazine* (vol. 58, No. 8), the Public Service Company of northern Illinois has installed buried pipe sections on a 160-acre tract at Mount Prospect, Ill., having a total capacity of 40 million cu ft of natural gas. Seamless pipe of high-carbon molybdenum-alloy steel was selected. The outside diameter is 24 in., wall thickness approximately  $\frac{1}{2}$  in., random lengths averaging 40 ft long. Both ends were forged into hemispherical shape at the fabricating plant of the National Tube Co. of Pittsburgh. After being stress-relieved, the units were hydrostatically tested at 2,800 psi. The volume of each container averages 109.5 cu ft and the weight 5,100 lb, and the capacity is 25,000 cu ft of natural gas at 2,240 psi.

Of particular interest was the effect of this high pressure on the compressibility of natural gas. It was found possible to force 230 cu ft into each cubic foot of space at 2,240 psi as contrasted with a calculated 160 cu ft. The capacity of the sections was thus increased some 40 per cent. The pipes were buried to minimize seasonal temperature changes. (At 2,240 psi, each 1°F temperature variation causes a 10-lb pressure change.)

## SECTION 7

### **THE TRANSFER AND GENERATION OF HEAT**



## CHAPTER 20

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### HEAT TRANSFER AND INSULATION

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## HEAT TRANSFER

### Methods of Heat Transmission

**1. Conduction.** When heat is transferred from one object in direct contact with another object, or from one portion of an object to another portion of the same object without appreciable motion of its molecules, this transfer is called conduction. Generally, heat transfer through solids is by conduction only.

**2. Convection.** Heat is transferred in a fluid (liquid or gaseous) by circulation of the fluid which carries the heat from one portion of the fluid to another portion.

**Natural convection** occurs in a fluid because of differences in density which are caused by temperature gradients in the fluid. The denser or heavier portion of the fluid sinks, and the less dense or lighter portion rises. The result of this action causes circulation within the fluid.

**Forced convection** occurs where there is an external force, such as a pump, to cause circulation.

**3. Radiation.** Radiant energy is given off in the form of waves that are similar to light but differ in frequency. If two bodies at differing temperatures are placed in an insulated enclosure, and the enclosure is evacuated of air, there is an interchange of energy between them. The body at the higher temperature loses heat to the colder body until equilibrium is attained. Even after equilibrium, the exchange of radiant energy continues, the radiation and absorption of each body then being equal.

### CONDUCTION<sup>1</sup>

For steady-state flow in one direction across a constant cross section of homogeneous solids (and fluids where no convection currents are present) the constant flow of heat can be calculated from the following expression:

$$q = \frac{kA(t_2 - t_1)}{L} = \frac{kA \Delta t}{L} \quad (20-1)$$

where  $q$  = rate of heat flow, Btu/hr

$k$  = thermal conductivity, Btu/(hr)(sq ft)(deg F per ft); see Table 20-1

$A$  = area of heat transfer, a plane perpendicular to direction of heat flow, sq ft

$t_2$  = higher temperature, deg F

$t_1$  = lower temperature, deg F

$\Delta t = t_2 - t_1$ .

$L$  = distance between points of  $t_1$  and  $t_2$ , ft

**Example:** Find the heat loss through a steel plate (1 per cent C) 8 ft by 4 ft by  $\frac{1}{2}$  in. thick with the higher temperature at 250°F and the lower temperature at 150°F.

**Solution:** Using Eq. (20-1), from Table 20-1  $k = 26.2$ ; also  $L = \frac{1}{2}/12 = 0.0416$  ft.

$$q = \frac{26.2 \times (8 \times 4)(250 - 150)}{0.0416} = 2,015,000 \text{ Btu/hr}$$

**Heat Transfer through Resistances in Series.** For steady flow, all the heat must travel through each of a series of resistances, making the heat current the same through each (Fig. 20-1). Temperatures automatically adjust themselves to provide this condition. This heat flow may be calculated from

$$q = \frac{t_a - t_d}{(L_a/k_a A_a) + (L_b/k_b A_b) + (L_c/k_c A_c)} \quad (20-2)$$

<sup>1</sup> GRISWOLD, J., "Fuels, Combustion, and Furnaces," pp. 316-331, McGraw-Hill Book Company, Inc., New York, 1946.

where  $q$  = rate of heat flow, Btu/hr

$k_a, k_b, k_c$  = thermal conductivity of each section (Fig. 20-1), Btu/hr/sq ft/deg F/ft  
 $A_a, A_b, A_c$  = area of heat transfer of each section; for constant cross section of heat conduction, such as through flat walls or slabs, these are equal, sq ft

$L_a, L_b, L_c$  = length of each section in the direction of heat flow, ft

$t_a, t_d$  = highest and lowest temperature, respectively, deg F

$$t_a - t_d = \Delta t$$

**Heat Transfer of Thick-walled Cylinders.** In many industrially important cases of heat transfer through resistances in series the areas are not equal or even approximately so. The most common case is that of heavily insulated pipe. The heat flow in this case

is

$$q = \frac{k A_{avg} (t_2 - t_1)}{L} = \frac{k A_{avg} \Delta t}{L} \quad (20-3)$$

where  $q$  = rate of heat flow, Btu/hr

$k$  = thermal conductivity, Btu/(hr)(sq ft)  
 (deg F per ft)

$t_2$  = higher temperature, deg F

$t_1$  = lower temperature, deg F

$\Delta t = t_2 - t_1$

$L$  = distance between points  $t_1$  and  $t_2$ , ft

$A_{avg}$  = average area, which may be calculated by the following expression

$$A_{avg} = \frac{A_2 - A_1}{2.3 \log_{10} (A_2/A_1)}$$

where  $A_2$  = outer surface area of cylinder, sq ft

$A_1$  = inner surface area of cylinder, sq ft

**Mean Temperature Differences in Heat Exchangers.** In a tubular exchanger (heater or cooler), the temperature difference changes continuously from one end of the apparatus to the other. The arithmetic average  $\frac{(t_{initial} + t_{final})}{2}$  is not the correct average value unless the temperature differences at the two ends are nearly equal.

Assuming constant specific heats and a constant over-all heat transfer, it can be shown that for certain important cases the proper temperature difference for use in the heat-transfer equation is the logarithmic mean temperature, as follows:

$$\Delta t_{lm} = \frac{\Delta t_1 - \Delta t_2}{2.3 \log_{10} (\Delta t_1/\Delta t_2)} \quad (20-4)$$

where  $\Delta t_{lm}$  = logarithmic mean temperature

$\Delta t_1$  = temperature difference at one end of the apparatus, deg F

$\Delta t_2$  = temperature difference at the other end of the apparatus, deg F

The logarithmic mean temperature applies to the following cases:

1. Concurrent and counterflow heat exchangers having a single pass for each fluid, as in concentric double-pipe apparatus.

2. Heaters and coolers in which one fluid is at constant temperature, such as a condensing vapor or a boiling fluid.

**Thermal conductivity** of a substance may be defined as the amount of heat (Btu) that flows in a unit of time (1 hr) through unit area of surface (1 sq ft) of unit thickness (1 ft) having unit difference in temperature between its faces (1°F). The resultant factor, usually designated as  $k$ , is different from the  $C$  factor or conductance

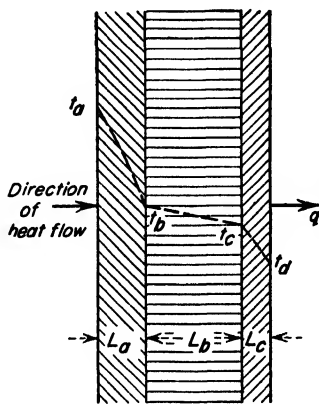


FIG. 20-1. Temperature drops through resistances in series (conduction).

in that the latter is the entire actual amount of heat flow in Btu per hour through 1 sq ft of the entire thickness of the material for a 1°F difference in the temperatures of its surfaces;  $k$ , on the other hand, represents the heat flow through unit thickness of 1 ft. As materials thicknesses of 1 ft were less convenient to the building trades than units of inches,  $k$  is frequently expressed as the flow for 1 in. thickness instead of 1 ft. In using tables and values, it is thus important to check for this very material difference.

**Table 20-1. Thermal Conductivity of Metals<sup>1</sup>**  
(Btu/hr sq ft deg F/ft thick)

Substance	Temp, deg F	$k$	Substance	Temp, deg F	$k$
<b>Metals:</b>					
Aluminum. . . . .	64	117	Mercury.	32	4 8
	212	119	Nickel	64	36
Antimony. . . . .	32	10 6		212	34
	212	9 7	Platinum	64	40 2
Bismuth. . . . .	64	4 7		212	41 9
	212	3 9	Silver	64	242
Cadmium. . . . .	64	53 7		212	238
	212	52 2	Tantalum .	64	32
Copper. . . . .	64	224	Tin . . .	64	36
	212	218		212	34
Gold. . . . .	64	169	Zinc . .	64	65
	212	170		212	64
Iron, pure . . .	64	39	<b>Alloys:</b>		
	212	36 6	Brass, yellow	32	49 4
Iron, wrought. .	64	34 9		212	61 5
	212	34 6	Brass, red	32	59 5
Iron, cast. . . . .	120	27 6		212	68 3
	216	26 8	Constantan (60% Cu, 40% Ni) ..	64	13 1
Steel (1% C). . . .	64	26 2		212	15 5
	212	25 9	Nickel silver . . . . .	32	16 9
Steel (13% Cr, 0.2% Ni)	626	19 3		212	21 5
Steel (18% Cr, 8% Ni)	626	14 8	Manganin (84% Cu, 4% Ni, 12% Mn) . . . . .	64	12 8
Steel (23% Cr, 12% Ni)	626	13 8		212	15 2
Lead. . . . .	64	20 1		64	14 5
	212	19 8	Platinoid. . . . .		
Magnesium.	32-212	92 0			

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 392, McGraw-Hill Book Company, Inc., 1941.

**Table 20-2. Thermal Conductivity of Insulating Materials at Moderate Temperatures ( $k$  Factor)<sup>1</sup>**

(Btu per hour per square foot, 1 ft thick, per degree F difference in temperature between faces)

Material	Weight, lb/cu ft	Temp, deg F						
		32	100	200	300	400	600	800
Asbestos . . . . .	36 0	0 087	0.097	0.110	0.117	0 121	0 125	0 130
Burned infusorial earth for pipe coverings . . . . .	12 5	0 043	0 046	0 052	0 057	0 062	0 073	0 085
Insulating composition (loose) . .	25 0	0 040	0 046	0 050	0 053	0 055		
Cotton . . . . .	5 0	0 032	0 035	0 039				
Silk hair. . . . .	9 1	0 026	0 030	0 034				
Silk . . . . .	6 3	0 025	0 028	0 034				
Wool . . . . .	8 5	0 022	0 027	0 033				
Pulverized cork . . . . .	10 0	0 021	0 026	0 032				
Infusorial earth, loose. . . . .	22 0	0 035	0.039	0 045	0 047	0 050	0.053	

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," 4th ed., p. 395, McGraw-Hill Book Company, Inc., New York, 1941.

Thermal conductivity varies widely. For metals and alloys,  $k$  is high, while for certain insulating materials such as cork, asbestos, and kapok,  $k$  is very low. Further, most insulating materials, except air spaces and the reflective types, are of a porous

nature consisting of combinations of solid matter with small air cells. The thermal conductivity of such materials will vary with many such factors such as density, mean temperature, size of the fibers or particles, degree and extent of bond between particles, moisture or oil present, and the arrangement of fibers or particles within the material. In the case of metals,  $k$  usually decreases with rising temperature, while for most other substances the reverse is true.

**Table 20-3. Thermal Conductivity of Various Insulating Materials ( $k$  Factor)<sup>1</sup>**  
(Btu per hour per square foot 1 ft thick, per degree F difference in temperature between faces)

Material	Max temp, deg F	Mean temp, deg F									
		100	200	300	400	500	600	800	1000	1500	2000
Asbestos felt, 40 laminations/in	700	0 033	0 037	0 040	0 044	0 048					
20 laminations/in..	500	0 045	0 050	0 055	0 060	0.065					
Corrugated asbestos (4 ply/in)	300	0 050	0 058	0 069							
85 % magnesia	600	0.039	0.041	0 043	0 046						
Diatomaceous silica:											
Brick...	1600	0 054	0 056	0 058	0 060	0.063	0 065	0 069	0 073		
Brick .	2000	0 127	0 130	0 133	0 137	0 140	0 143	0.150	0 158	0 176	
Brick	2500	0 128	0 131	0 135	0 139	0 143	0.148	0.155	0.163	0.183	0 203
Powder (18 lb/cu ft)		0 039	0 042	0 044	0 048	0 051	0 054	0.061	0 068		
Rock wool .		0 030	0 034	0 039	0.044	0 050	0 057				

NOTE: Other values: Asbestos cement, 0.1; 85 % magnesia cement, 0.05, asbestos and rock wool cement, 0.075 approximately.

<sup>1</sup> MARKS, LIONEL S. "Mechanical Engineers' Handbook," 4th ed., p. 395, McGraw-Hill Book Company, Inc., New York, 1941.

**Table 20-4. Thermal Conductivity of Materials for Refrigeration and Building Insulation ( $k$  Factor)<sup>1</sup>**

(Btu per hour per square foot, 1 ft thick, per degree F difference in temperature)

Material	Appar-ent den-sity, lb/cu ft	Mean temp, deg F	$k$	Material	Appar-ent den-sity, lb/cu ft	Mean temp.	$k$
Cabots quilt	4 0	86	0 022	Balsa wood	2 2	86	0 023
Cork (granulated)	7.3	24	0.028	Cork board	10 0	86	0 025
Cork, granulated (baked)	8 1	86	0 026	Hair felt	11.0	86	0.022
Dry Zero (kapok)	1.0	86	0 020	Hairinsul	6 3	86	0 023
Flaxlinum and Fiberfelt	11 2	86	0.028	Linofelt	11 2	86	0 025
Gypsum, molded and dried	78 0	68	0 250	Lith .	14 3	86	0 033
Insulte, Celotex, etc	16 0	86	0 028	Rock cork...	16.0	86	0 028
Insulex or Pyrocel.....	8 0	86	0 029	Rock wool..	14.0	86	0.023
	12 0	86	0 037	Sil-O-Cel...	10 6	86	0.026
	18 0	86	0 049	Thermofil	34 0	86	0 050
	24 0	86	0 064	Wool felt	20 6	86	0 030
	30 0	86	0 083	Vermiculite (expanded)	6 2	42	0.027

<sup>1</sup> MARKS, LIONEL S. "Mechanical Engineers' Handbook," 4th ed., p. 394, McGraw-Hill Book Company, Inc., New York, 1941.

**Underground Conditions of Conductivity and Temperature.** Underground conditions of conductivity and temperature are of importance for such applications as (1) the earth as a heat source for heat-pump applications, (2) the perimeter and ground-slab loss for floor-panel-heating systems, and (3) the ground losses together with



**Table 20-5. Resistance to Heat Flow of Various Insulating Materials**

<i>Material</i>	<i>Resistance<sup>a</sup></i>
Blanket and bat insulation, avg . . . . .	4 07
Kapok between burlap or paper . . . . .	4 17
Fireproofed cotton fibers . . . . .	4 17
Hair felt between paper layers . . . . .	4 00
Eel grass between paper . . . . .	4 00
Wood fiber between paper . . . . .	4 00
Loose fill and blown-in insulation, avg . . . . .	3 65
Ceiba fibers (kapok) . . . . .	4 35
Mineral wool from silica . . . . .	3 70
Mineral wool from slag . . . . .	3 70
Glass wool . . . . .	3 70
Rock wool . . . . .	3 70
Expanded vermiculite (best grade) . . . . .	3 12
Granulated cork . . . . .	3 22
Vegetable fiber insulating board, avg . . . . .	3 06
From sugar-cane fiber . . . . .	3 03
From cornstalks . . . . .	3 03
From exploded wood fibers . . . . .	3 12
Slab insulation, avg. . . . .	2 71
Sugar-cane fiber in asphalt membrane . . . . .	3 33
Hog hair with film of asphalt . . . . .	3 57
85 % magnesia . . . . .	1 96
Shredded wood and cement . . . . .	2 17
Foamglas (from manufacturers' literature) . . . . .	2 50
Reflective insulation, <sup>b</sup> avg . . . . .	4 01
Ceiling, heat flow up (winter) . . . . .	3 70
30 deg slope, heat flow up (winter) . . . . .	4 00
Walls . . . . .	4 35

<sup>a</sup> Resistance to heat flow is the reciprocal of conductivity ( $k$ ), in which  $k$  = heat units transmitted per hour per degree difference in temperature per inch of thickness per square foot of material. Thus the higher the value of resistance shown, the better the insulation.

<sup>b</sup> Reflective insulation is higher in resistance by two to three times with the heat flow down (summer).

**Table 20-6. Thermal Conductivity of Soil<sup>1,2</sup>**

	Btu/hr/sq ft/deg F/ft	
	Source 1	Source 2
Fairly dry soil . . . . .	0 25-0 35	0 14-0 80
Wet weather, some drainage . . . . .	0 50	
Heavy rains, ground not flooded . . . . .	0 65	
Ground marshy or constantly soaked . . . . .	1 00	
Dry sandy soil . . . . .	0 16	0 21
Damp clay and sand . . . . .		0 92
Clean yellow sand:		
Dry . . . . .	0 17	0.19-0.22
2 per cent moisture . . . . .	0 20	
4 per cent moisture . . . . .	0 28	
6 per cent moisture . . . . .	0.40	
8 per cent moisture . . . . .	0.56	
Yellow sand and clay:		
2 per cent moisture . . . . .	0.16	
4 per cent moisture . . . . .	0 17	
6 per cent moisture . . . . .	0.20	
8 per cent moisture . . . . .	0 26	
10 per cent moisture . . . . .	0 35	
12 per cent moisture . . . . .	0 51	
14 per cent moisture . . . . .	0.79	
Soil wet, min. . . . .		0 85
Soil wet, avg . . . . .		1.69
Soil wet, max. . . . .		2 69

<sup>1</sup> MAKER, F. L., Special Problems in the Flow of Viscous Fluids, Standard Oil Co. of California.

<sup>2</sup> Oil Gas J.

floor slab temperatures for basementless houses where other heating methods exclusive of floor-panel systems are used.

**Thermal Conductivity of Soil.** The conductivity of soil varies greatly according to the consistency, moisture, and density conditions. Test results are not always in complete accord, not because of errors of observation, but because of the difficulty

of accurately defining the several variables. Table 20-6 shows typical results as reported by two investigators. In addition, Algren<sup>1</sup> comments:

1. At a constant moisture content, ground thermal conductivity increases with an increase in dry density. The rate of increase is fairly constant and is independent of the moisture content.
2. At a constant dry density, thermal conductivity increases with an increase in moisture content.
3. For unfrozen soil, it increases with an increase in mean temperature.

Table 20-7. Conductivity of Silt-clay Soils<sup>1</sup>

Soil density, lb/cu ft	Moisture, per cent	Mean temp, deg F	k, Btu/sq ft/hr/deg F/in.	Soil density, lb/cu ft	Moisture, per cent	Mean temp, deg F	k, Btu/sq ft/hr/deg F/in.
93 0	1 23	70 3	2 23	92 4	16 70	40 1	8 78
93 0	1 23	40 1	2 16	92 4	16 70	25 1	11 17
93 0	1 23	24 9	2 14	92 4	16 70	-19 9	10 97
93 0	1 23	-19 9	2 15	92 4	23 0	70 0	11 00
92 4	16 70	70 1	9 14				

<sup>1</sup> KERSTEN, MILES S., *Heating Piping Air Conditioning*, June, 1949.

4. Frozen soil at low moisture content shows very little change; in general, for soils of high moisture content it shows an increase for a decrease in temperature.

5. When changing from unfrozen to frozen soil, the conductivity varies according to the moisture content. For dry soils it does not change; for soils of low moisture content, it decreases; and, with soils of high moisture content, it increases.

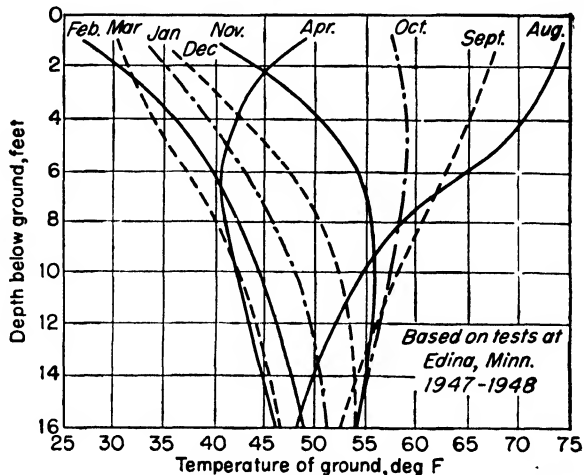


FIG. 20-2. Ground temperatures at various depths and months. (Algren, A. B., *Ground Temperatures as Affected by Weather Conditions*, ASHVE Journal Section, *Heating, Piping & Air Conditioning*, June, 1949, pp. 111-116. Used by permission.)

Tests upon which these conclusions were based were conducted by Miles S. Kersten and are summarized in part in Table 20-7.

*Ground Temperatures at Various Depths.* Figure 20-2 summarizes a study of ground-temperature conditions throughout the 1947-1948 heating season as reported by Algren.<sup>2</sup> The soil at the Minnesota test location was of the sand and clay type,

<sup>1</sup> ALGREN, A. B., *Ground Temperatures as Affected by Weather Conditions*, *Heating, Piping, Air Conditioning*, June, 1949, pp. 111-116. Used by permission.

<sup>2</sup> *Loc. cit.*

at some points bare, and at some covered with sod. The insulating effects of the sod were quite apparent. An interesting point is that the ground at 16 ft depth is warmest in November and coldest in April. This is due to time lag.

**Surface-well Temperatures.** Figure 20-2 shows approximate well temperatures to be expected at depths of 30 to 60 ft for various parts of the United States (exclusive of thermal regions).

**Heat Loss to the Ground.** In designing floor-type radiant-heating systems, it is standard practice to use an arbitrary figure of 15 per cent of all other losses to cover the heat escaping to the ground. This has proved adequate for outside temperatures down to  $-15^{\circ}\text{F}$ .

Where the installation goes into operation for the first time in freezing weather, this allowance may be inadequate; but, after some hours of operation, the slab comes up to temperature and no lack of capacity will be noticed from that time on.<sup>1</sup>

The question of insulation under floor slabs should be decided after a comparison of costs with anticipated savings based upon the above factor. Slab edges should, however, be insulated, and such insulation should be carried well down the inside of footings (2 ft seems a reasonable minimum under normal weather conditions).

## CONVECTION

**Surface Film Coefficients.<sup>2</sup> Convection Mechanism.** There are two general mechanisms by which a fluid may travel through a pipe or duct: (1) viscous, laminar, or streamline; and (2) turbulent motion.

1. In **viscous flow**, all particles of the fluid travel parallel to the axis of the pipe.

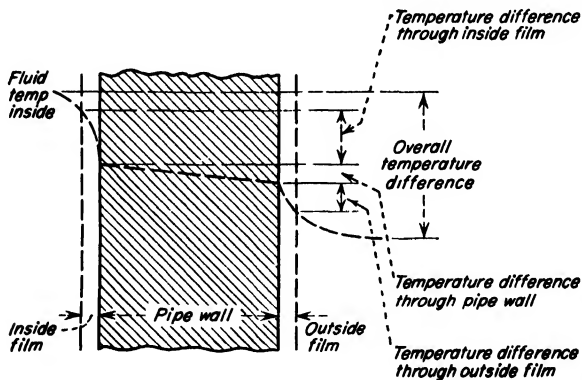


Fig. 20-3. Temperature drops through fluid films and pipe wall.

2. In **turbulent flow**, elements in the main portion of the stream move back and forth over the cross section of the pipe in a random motion, in addition to their net flow along the axis of the pipe.

Even in highly turbulent flow there is a thin fluid layer or film adjacent to the pipe wall, which remains in viscous flow. Heat must flow through the film by the mechanism of conduction, before being swept away by eddies in the rapidly moving main body of the stream. Heat-transfer film coefficients are calculated from experimental heat-transfer data.

Heat transfer through a pipe wall can be calculated from the following expression (Fig. 20-3):

$$q = \frac{t_i - t_o}{(1/hA)_i + (L/kA_{av})_w + (1/hA)_o} \quad (20-5)$$

<sup>1</sup> CONNER, W. A., *Heating, Piping, Air Conditioning*, vol. 20, No. 6, p. 105, June, 1948.

<sup>2</sup> GRISWOLD, J., "Fuels, Combustion, and Furnaces," pp. 316-333, McGraw-Hill Book Company, Inc., New York, 1946.

where  $q$  = rate of heat flow, Btu/hr  
 $t_i$  = temperature inside pipe, deg F  
 $t_o$  = temperature outside pipe, deg F  
 $\Delta t = t_i - t_o$

$h_i$  and  $h_o$  = film coefficients for the inside and outside of the pipe, respectively,  
 Btu/hr/sq ft/deg F

$A_i$  and  $A_o$  = inside and outside areas of the pipe, respectively, sq ft

$A_{avg}$  = average area of pipe, sq ft

$k$  = thermal conductivity of pipe

In the case of metallic heating and cooling tubes surrounded by and filled with fluids, the fluid films ordinarily offer much greater resistance to heat transfer than does the tube wall. The common ranges of fluid film coefficients are given in Table 20-8.

Table 20-8. Fluid Film Coefficients<sup>1</sup>

	Usual ranges of values $h$ , Btu/hr/sq ft/deg F			
	Gases	Water	Nonviscous liquids	Viscous liquids
Inside pipes.	10-50	200-2,000	50-500	10-100
Outside pipes:				
Natural convection	1-3	20-200		2-50
Forced convection	5-20	100-1,000	50-200	10-100
Boiling liquid:				
Inside pipes		500-5,000		
Outside pipes		300-9,000	200-2,000	
Condensing vapor		1,000-10,000	200-400	50-100

<sup>1</sup> Loc. cit.

Thin films of foreign material such as dirt, scale, or products of corrosion frequently introduce appreciable resistances to heat transfer. They present comparatively rough surfaces and maintain thicker films than would otherwise exist. Typical values of "fouling coefficients" to be included in the summation of resistances to heat transfer are given in Table 20-9.

Table 20-9. Fouling Coefficients<sup>1</sup>

	Usual Range of Values $h$ , Btu/Hr/Sq Ft/Deg F
Steam	1,500-3,000
Clean water	500-2,000
Dirty water	150-500
Petroleum vapors and condensates	200-2,000
Petroleum residuals and crudes	100-200

<sup>1</sup> Loc. cit.

**Over-all Heat-transfer Coefficients.** For convenience in solving heat-transfer problems, thermal resistances in series through solids, scale, and fluid films may be combined into a single total resistance. The over-all heat-transfer coefficient is then defined as  $U$  in the equation

$$q = UA(t_2 - t_1) = UA \Delta t \quad (20-6)$$

where  $q$  = rate of heat flow, Btu/hr

$U$  = over-all heat-transfer coefficient, Btu/hr/sq ft/deg F

$t_2$  = higher temperature, deg F

$t_1$  = lower temperature, deg F

$\Delta t = t_2 - t_1$

The usual ranges of over-all heat-transfer coefficients are contained in Table 20-10.

**Table 20-10. Over-all Heat-transfer Coefficients<sup>1</sup>**  
(Btu/hr/square foot/deg F)

	State of controlling resistance		Typical fluid	Typical apparatus
	Free convection $U$	Forced convection $U$		
Liquid to liquid .....	25-60 5-10	150-300 20-50	Water Oil	Liquid-to-liquid heat exchangers
Liquid to gas atmospheric pressure). ....	1-3	2-10	.....	Hot-water radiators
Liquid to boiling liquid. ....	20-60 5-20	50-150 25-60	Water Oil	Brine coolers
Gas (atmospheric pressure):				
To liquid . ....	1-3	2-10	.. . . .	Air coolers, economizers
To gas . . . . .	0 6-2	2-6	...	Steam superheaters
To boiling liquid. ....	1-3	2-10	.	Steam boilers
Condensing vapor to liquid. ....	50-200 10-30 40-80 .....	150-800 20-60 60-150 15-300	Steam-water Steam-oil Organic vapor-water Steam-gas mixture	Liquid heaters and condensers
Condensing vapor to gas (atmospheric pressure)	1-4	2-10	.....	Steam pipes in air, air heaters
Condensing vapor to boiling liquid	40-100 300-1,200 50-150	... ... .	Steam-water Steam-oil	Scale-forming evaporators

<sup>1</sup> *Loc. cit.*

### RADIATION<sup>1</sup>

Since thermal radiation is akin to visible light, most solids, liquids, and gases that are transparent to light will transmit some fraction of heat rays that may strike them. Opaque materials are opaque to radiant heat or nearly so, and highly reflective surfaces reflect heat rays efficiently. There are some exceptions to these observations, but in general the transparency of a substance is lower for heat than for light rays. Radiant-heat transfer is usually significant wherever a high-temperature surface capable of radiating can "see" another surface at a lower temperature.

**Surface Emissivity.** The term emissivity  $e$  is the ratio of heat emitted by an actual surface to that of a black body of the same area and at the same temperature. A black body is a theoretically perfect radiator which will emit a definite maximum rate per unit area for any given temperature.

Emissivities of polished metal surfaces are very low but are greatly increased by the presence of slight films of oxide or of tarnish. Emissivities of engineering materials and equipment surfaces under conditions of use are between 0.7 and 0.9 in most cases.

**Surface Absorptivity.** Of the radiation striking a surface, part is reflected, and the remainder is absorbed. A perfect absorbing surface must therefore be totally unreflective and is also designated a black body. Absorptivity  $a$  is the fraction of incident radiant energy which a surface absorbs.

For all practical purposes, the coefficients of emissivity and absorptivity are so numerically close that one may be substituted for the other with but slight error.

<sup>1</sup> *Loc. cit.*

The **Stefan-Boltzmann law** for radiant heat emitted from the surface of a body is as follows:

$$\frac{q_r}{A} = 0.173e \left( \frac{T}{100} \right)^4 \quad (20-7)$$

where  $q_r$  = total heat loss by radiation, Btu/hr

$A$  = area of radiating surface, sq ft

$e$  = emissivity, used as a constant

$T$  = absolute surface temp =  $(460 + \text{deg F})$

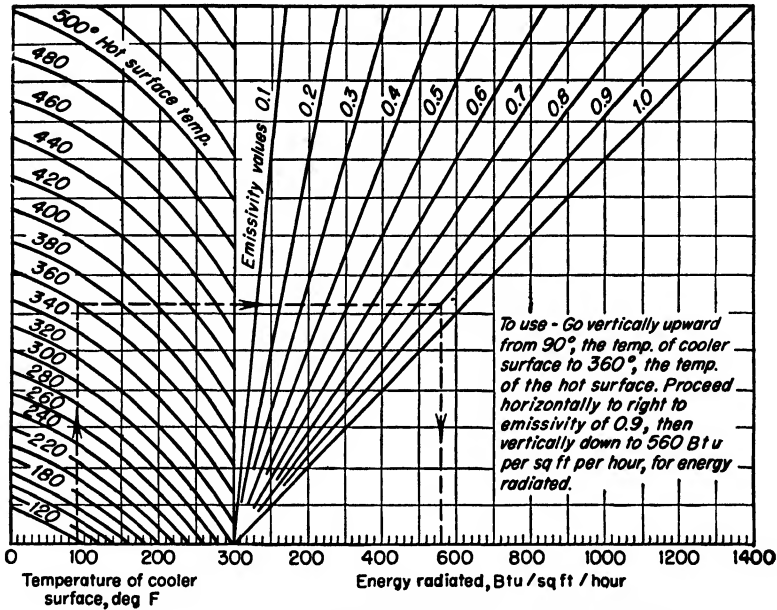


FIG. 20-4. Heat transmitted by radiation. (Trans. ASME.)

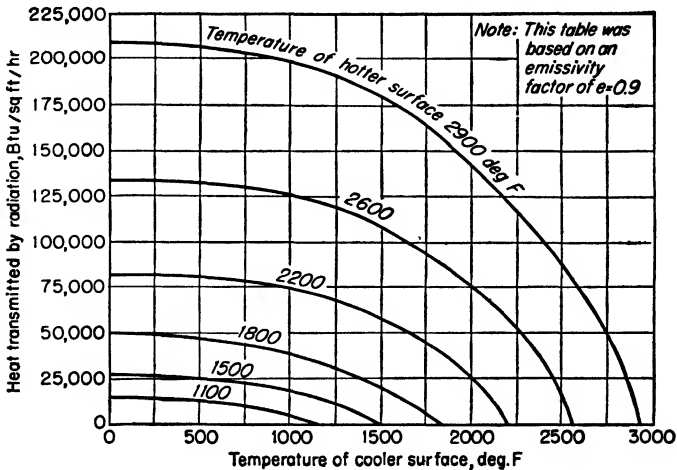


FIG. 20-5. Heat transfer by radiation at various temperatures.

Table 20-11. Emissivity Values<sup>1</sup>

	Temp, deg F						
	100	200	300	400	500	600	700
Polished silver	0 0221	0 0252	0 0292	0 0315	0 0295	0 0308	0 0312
Lampblack	0 945	0 945	0 945	0 945	0 945	0 945	0 945
Asbestos paper	0 930	0 934	0 943	0 955	0 929	0 938	0 943
Rough steel plate	0 945	0 950	0 955	0 961	0 969	0 975	0 975
Aluminum-surfaced roofing	0 216						
Polished brass	0 096	0 096	0 098	0 098	0 096	0 096	
Flat black lacquer	0 960	0 98					
Black lacquer	0 80	0 95					
White lacquer	0 80	0 95					

<sup>1</sup> HEILMAN, R. H., Surface Heat Transmission, *Trans. ASME*, vol. 51, FSP-41, 1929.

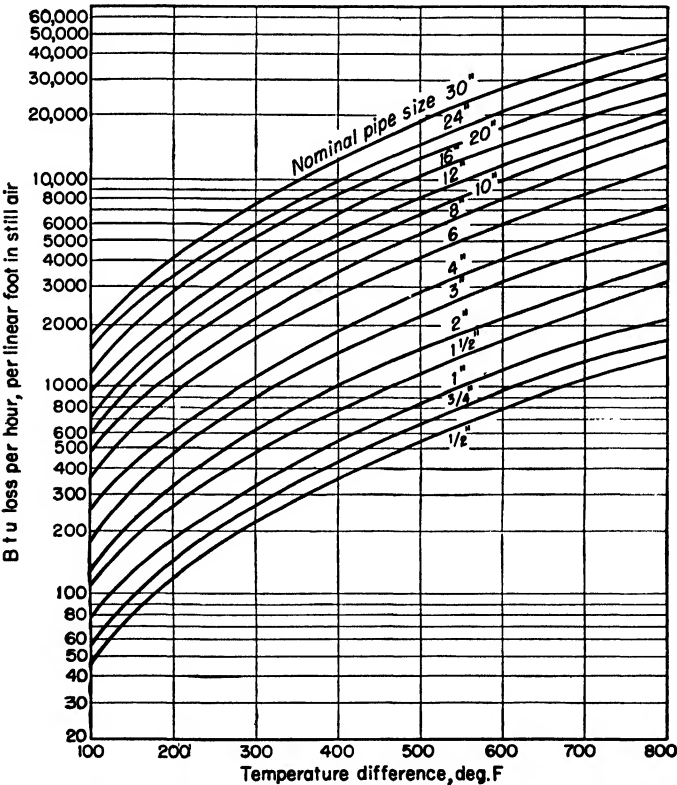


FIG. 20-6. Heat loss from bare (uninsulated) pipe. Total Btu per hour per linear foot in still air.

Equation (20-7) assumes that all points of the surface are at the same temperature and that its emissivity is uniform. It is exact only for surfaces having no concavities; i.e., no portion of the surface “sees” any other portion. It gives **total** radiation. When the surroundings are at any temperature above absolute zero, a body receives some radiation from surroundings. However, if the surface temperature of the body

Table 20-12. Heat Loss from Bare Metal Surfaces

Temperatures		Heat losses		Temperatures		Heat losses	
Temp difference, deg F	Operating temp, deg F (50° air)	Btu loss /deg F difference/sq ft/hr	Total loss, Btu/sq ft /hr	Temp difference, deg F	Operating temp, deg F (50° air)	Btu loss /deg F difference/sq ft/hr	Total loss, Btu/sq ft /hr
100	150	2 15	215	650	700	6.32	4,111
150	200	2 40	360	700	750	6.80	4,760
200	250	2 67	533	750	800	7.27	5,456
250	300	2 95	737	800	850	7.75	6,200
300	350	3 29	978	850	900	8.23	6,991
350	400	3 63	1,269	900	950	8 70	7,830
400	450	4 04	1,614	950	1000	9 18	8,716
450	500	4 46	2,007	1000	1050	9 65	9,650
500	550	4 92	2,460	1050	1100	10 12	10,631
550	600	5 38	2,959	1100	1150	10 60	11,660
600	650	5.85	3,510	1150	1200	11.06	12,736

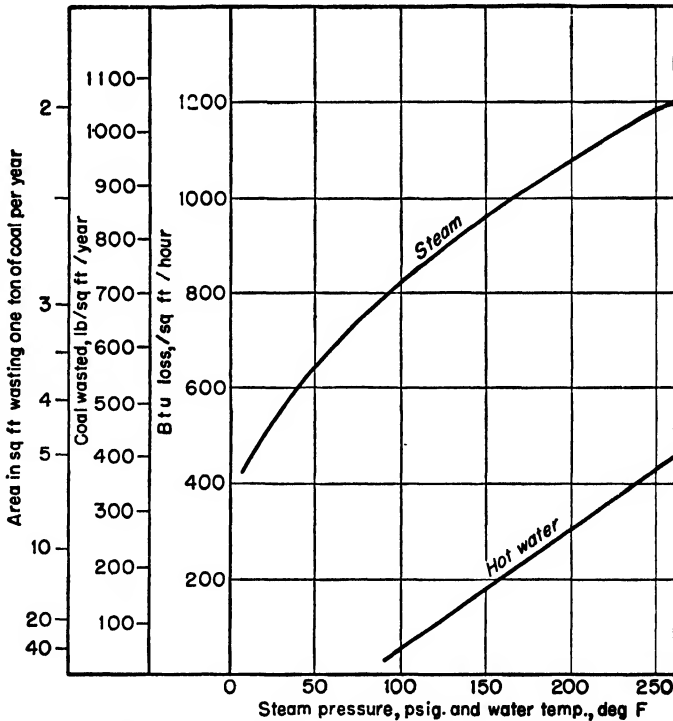


FIG. 20-7. Heat and coal lost by heat loss from uninsulated pipe surfaces.

is as much as several hundred degrees higher than the surroundings, Eq. (20-7) gives a close approximation of actual loss by radiation.

Figure 20-4<sup>1</sup> is a graphical method of calculating the energy radiated from a surface at higher temperature to a cooler surface, at various emissivities. Table 20-11 gives the emissivity values of various surfaces for a temperature range of 100 to 700°F.

<sup>1</sup> HEILMAN, R. H., Surface Heat Transmission, *Trans. ASME*, vol. 51, FSP-41, 1929.



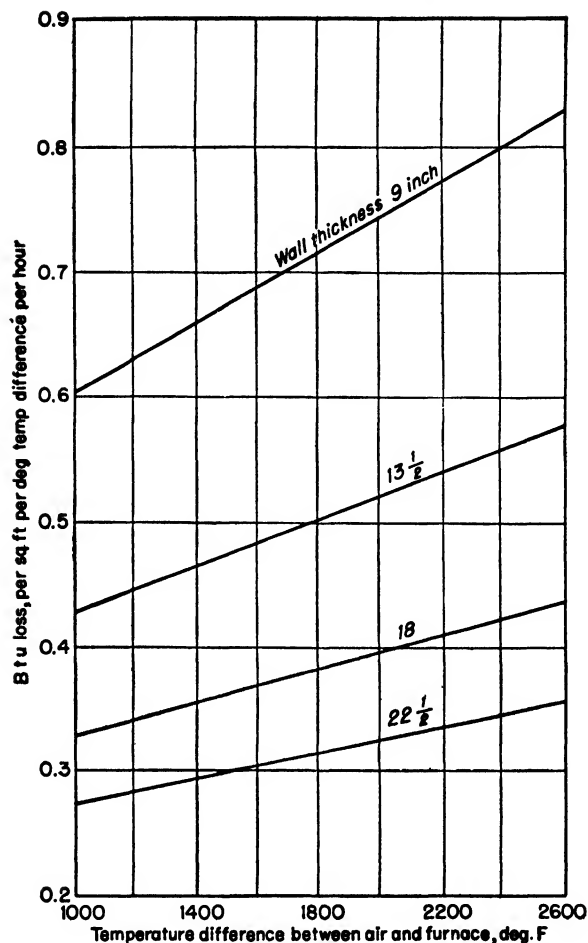


FIG. 20-8. Heat loss through uninsulated firebrick walls. NOTE: For total loss multiply value from table  $\times$  temperature difference  $\times$  area.

### EFFECT OF WIND VELOCITY ON HEAT LOSSES

Assuming that most insulation will be installed indoors, heat losses discussed in this chapter are all based on still-air conditions. However, even moderate winds and air currents have a marked effect upon such losses, particularly on bare surfaces. They should thus always be taken into account wherever air currents are known to exist or are anticipated.

As is shown in Fig. 20-9, the losses from bare surfaces vary with the wind velocity and pipe-temperature difference. With a 12 mph wind, a characteristic annual average wind velocity in the United States (see Fig. 10-6 for a map of United States annual wind), the heat loss from bare surfaces will be from 1.5 to 2.5 times as much as in still air.

On insulated pipes or surfaces with a 30 mph wind, the maximum increase in heat loss due to the wind is about 15 per cent with 1 in. insulation, 10 per cent with 2 in., and 5 per cent with 3 in. It is thus apparent that the increase in heat loss is not only

much less with insulated pipes but also that the thicker the insulation the less the effect of the wind in increasing the loss. However, unless the insulation is reasonably impervious to the flow of air, the improvement will be decreased.

A common fault in insulation, particularly in applying fitted jackets as on domestic boilers, is to allow air space between the metal and the insulation. If not completely sealed at the top and bottom, convection currents may be set up to simulate the effect of wind with corresponding losses.

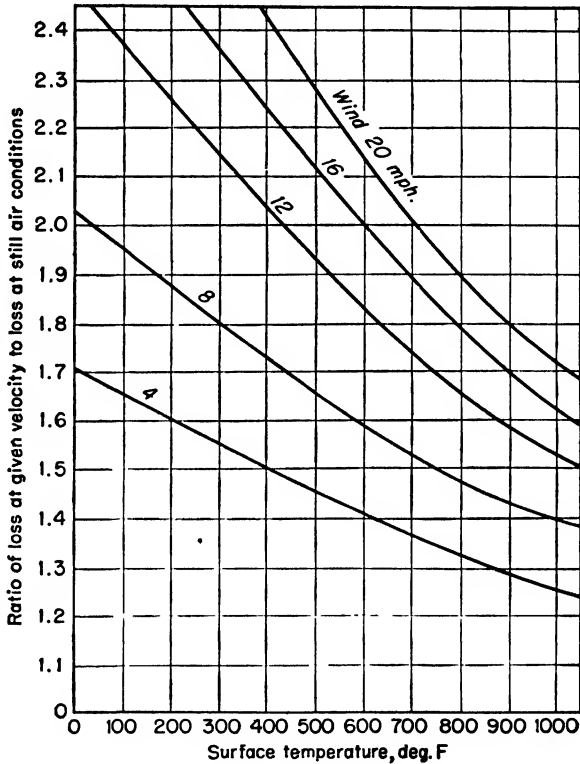


FIG. 20-9. Bare-surface losses at various wind velocities.

## INSULATION

There is a wide variation in the three properties most important in a material to be used for thermal insulation—physical resistance to heat, thermal conductivity, and mechanical strength. When methods of processing and manufacture are included, the choice becomes even wider. In general, insulating materials having a high refractory value are the lower in insulating value. It is also usual that materials for higher temperatures are more expensive.

The proper insulation for a given application is one which has a high enough refractory value to withstand the temperature requirements yet which has insulating value sufficiently high to justify its cost. Requisites for an insulating material, named in the order of their importance, may thus be said to include:

1. Ability to withstand the temperatures and physical conditions to which subjected.

2. Ability to provide an insulating effect commensurate with the need for insulation.

3. Installed cost sufficiently low to justify the insulation.

While cost and fuel saving are usually the prime considerations of items 2 and 3 and are thus commonly balanced against each other, such is not always the case. The delivery of dry steam for processing, the preservation of food in refrigeration, the maintenance of superheat without having to change the superheater design, or the protection of lines from freezing are all examples that may transcend net cost in importance. They would thus play an important part in a determination of the material or thickness of insulation.

### RAW MATERIALS USED AS INSULATING MEDIUMS

Among materials commonly processed into insulating mediums are:

**Asbestos.** A variety of mineral amphibole deriving its name from a Greek word meaning incombustible. The original source of asbestos was the mineral actinolite, but the variety of serpentine known as chrysotile now furnishes most of the commercial asbestos. Occurrence is in rock form, but the fibers are readily separated into fibers of varying lengths or into fibrous masses or seams. Tremolite and actinolite are also employed as asbestos where available. Asbestos, used alone or in combination with various other materials such as cotton, is processed into an almost innumerable number of forms and is used for many widely divergent purposes. The United States, consuming over 60 per cent of total production, produces only 4 per cent. Other important producers are Canada, Russia, and Africa. Currently the lack of discovery of any important new deposits and the expansion of use is causing considerable concern within the trade and stimulating activity toward as yet unfulfilled attempts to develop substitutes.

**Cork.** A thick spongy bark of a species of oak tree, *Quercus suber*, native to Spain and Portugal. It is tough, elastic, and impervious. Lacking in capillaries, it does not absorb moisture. The material has a cellular structure with more than 50 per cent of the volume in air cells. The construction is unusual in that each cell is in physical contact with 14 other cells to contribute to its low thermal conductivity. It is one of the lightest of solids, with a specific gravity of 0.15 to 0.24. While charring begins at 250°F, it ignites only in contact with flame. **Corkboard**, compressed from granulated cork, has a heat conductivity of 0.304 Btu/hr/sq ft/in. thick per degree difference in temperature, about one-third that of wood.

**Diatomaceous Earth.** Also known as infusorial earth, kieselguhr, diatomite, and, in a pure form, Tripoli. A class of compact, granular, or amorphous mineral composed of hydrated silica of the same chemical composition as the opal. Origin thought to be minute siliceous shelly remains accumulated at the bottom of ancient lakes. In reality, the material is not "earthy," and a preferred name is "diatomite." Pure diatomite has a porosity of 90 per cent of its volume. It has great absorptive powers, holding up to five times its volume of water. Apparent density, in powdered form, 8 to 8.5 lb per cu ft; tamped, 15 to 17 lb; natural, 12 to 17 lb. It withstands high temperatures. As an insulation, it is available in either natural or calcined form. Bricks or blocks are both sawed from the raw rock or molded from the crushed or loosely found material. In natural bricks the conductivity varies widely with and across the grain. For example, Johns-Manville lists 1.13 as the conductivity with heat flow parallel to the brick strata and 0.79 perpendicular, both being for mean temperatures of 1000°F. Calcining or baking increases resistance to heat but likewise increases the conductivity. Natural diatomite withstands up to about 1600°F and has a conductivity, across the grain and at 1500°F, of 0.90; highly calcined diatomite withstands temperatures to 2500°F and has a conductivity, at 1500°F no-

grain effect, of 2.19. As various intermediate degrees of calcining are available, it is obvious that these represent the extremes of a continuous range of values. Calcining also increases the density or weight with a maximum of about 40 lb per cu ft. A diatomite manufactured by Philip Carey Co., called **Dicalite**, is used as a heat-insulating cement and as a filler for walls. Calcined bricks made by Johns-Manville are known as **Sil-O-Cel** (Johns-Manville also sells natural bricks under the same name). **Suprex** of Johns-Manville is calcined diatomite bonded with asbestos fiber; it withstands to 1900°F. A calcined brick is also made by Armstrong Cork Co. Principal producing states are California and Oregon.

**Infusorial Earth** (see Diatomaceous Earth).

**Kapok.** A silky fiber obtained from the silk-cotton tree, common in most tropical countries. It is extremely light and resilient. The fiber, which is obtained from the bolls, is long, white, and silky, similar in appearance to cotton but too brittle for spinning. **Dry-Zero**, marketed by the Dry-Zero Corp., is an insulating material made from kapok. The carded fiber bat is enclosed in fiberboard for use in refrigerating cabinets and similar purposes.

**Kieselguhr** (see Diatomaceous Earth).

**Magnesium Carbonate.** A light white insoluble powder with a specific gravity of 3.10. The most popular commercial insulation for steam lines and similar service, 85% magnesia combines carbonate of magnesia and asbestos, desirably in the ratio of 85 per cent hydrated basic magnesium carbonate, 10 per cent asbestos fiber, and not over 5 per cent other inerts. The material is available in a wide variety of forms from several different manufacturers and is suitable for temperatures up to about 600°F.

**Mineral Wool.** Made by mixing stone from the molten slag from blast furnaces and subjecting the molten mixture to the disintegrating effect of steam or air under high pressure. The steam or air jet breaks the molten slag stream into tiny globules and propels them through the air at high speed. In their flight they are drawn into fibers of minute diameter. Mineral wools, as made from various substances of the same general classification, are also known as **rock wool**, **slag wool**, and **glass wool**. They are available in several forms including loose, bats, pellets, blankets, blocks, and pipe covering. A rock wool, made from high-silica limestone, is marketed by Johns-Manville as **Banrock** and is recommended for temperatures up to 1000°F. **Zerofil**, of the same company, for temperatures below 100°F, is a rock wool coated with asphalt to make it resistant to moisture. **Glass wool** is a lightweight insulating material composed of glass fiber as made from special glass forced through minute orifices or spinnerettes, similar to the manner in which rayon is spun. The fiber, about 0.001 in. in diameter, forms a loose blanket which can be woven into cloth, fabric, etc.

**Vermiculite.** May be made from any number of micaceous minerals, as kerrite, maconite, etc., which are hydrous silicates derived from the alteration of some form of mica. Called vermiculite because the scales open out when heated, sometimes producing long wormlike forms. Upon calcination at 1750°F, vermiculite expands at right angles to the cleavage into a fluffy mass having a volume of some sixteen times that of the original mineral. Color changes from a yellowish to brown to silvery or golden depending upon the temperature. A plaster made from 60 per cent vermiculite, 30 per cent plaster of paris, and 10 per cent asbestos will withstand red heat without disintegrating. **Zonolite** is an exfoliated vermiculite marketed by the Zonolite Co.

## GENERAL USES AND SELECTION OF INSULATION

Insulation is used to retard heat flow wherever it is desired to maintain a temperature either higher or lower than the surroundings.

In **industrial furnaces**, fuel saving is the principal benefit, with corollary advantages

of improvement in product quality due to the more uniform distribution of heat and more accurate temperature control. Additional advantages include increased capacity of equipment, protection of brickwork from rapid temperature changes, reduction of internal strains and cracking, and an improvement in working conditions around the equipment.

In boilers, insulation is even more essential over bare metal surfaces than over brickwork because of the greater rate of heat transfer.

**Steam-pipe insulation** reduces condensation, permitting the delivery of drier steam.

In refrigerated equipment, a ton of refrigeration, equivalent to the removal of 288,000 Btu per 24 hr, costs approximately ten times as much as the equivalent number of Btu as produced for heating purposes. The necessity and economic justification for much heavier insulation on low-temperature work than is customary for high temperatures are therefore apparent. Furthermore, many forms of cold storage demand temperature controls through a narrow range, which dictates the desirability of adequate insulation.

**Selection of Insulation.** The efficiency of a commercial insulation depends primarily on the small voids which it contains. In order to be most effective, these voids must be enclosed and so small that circulation within them, and radiation across them, will be at a minimum. This becomes particularly important at high temperatures because of the rapid increase in both convection and radiation at high temperatures.

To be adaptable, insulation should be of such form as to be easily applied, it must be able to withstand the highest temperatures to which it is ever to be subjected, and it must be sufficiently strong and durable to assure long life under the physical conditions to which subjected.

Since no one material or shape could possibly meet all such conditions, which may conceivably involve a temperature range from many degrees below zero to some 3000°F or more, most of the larger manufacturers offer a choice of products and shapes as made from such raw materials as asbestos, magnesium carbonate, diatomaceous silica, refractory clays, and mineral wool. These are processed into such shapes as sectional pipe covering, insulating sheets, blocks, bricks, and blankets, insulating cements, fills, paper, and felt. A selection must be made from these based upon the particular physical conditions to be met.

**Temperature Range.** At virtually every temperature, a choice of several materials is available. A final decision as between these must be made on a basis of the full requirements as listed above, as correlated with the properties of the several products as discussed and shown in pages following.

**Thickness of Heat Insulation.** The economic thickness of pipe and boiler insulation depends primarily upon the temperature and the cost of heat. The economical thickness of pipe insulation also depends on pipe size. While small pipes have to be more heavily insulated to give the same savings of heat, larger pipes should actually be provided with the heavier insulation for maximum net savings; i.e., a 1-in. pipe with 1 in. of insulation will lose heat more rapidly per square foot of pipe area than a 10-in. pipe with the same thickness of insulation; because the outer surface of the insulation on the 1-in. pipe is nearly 200 per cent greater than that of the pipe, with the outside area of the insulation on a 10-in. pipe less than 20 per cent greater. However, the net saving takes into account the cost per year of effecting the savings as subtracted from the savings. Since the insulation on a 1-in. pipe costs from  $1\frac{1}{2}$  to 3 times as much per square foot of pipe surface as that on a 10-in. pipe, and since each inch of thickness on a 10-in. pipe saves more heat than the same insulation on a 1-in. pipe, it follows that it pays to insulate the larger pipe the more heavily.

**Efficiency of Insulation.** The expression of the efficiency of insulation furnishes a means of comparing the savings effected by insulation with bare-pipe losses. Also the relative values of various insulations may be determined by comparing either their efficiencies or their heat losses. (The latter are shown for bare surfaces and the more common types of insulation in tables on the pages following.)

The efficiency of an insulation is obtained by subtracting the heat loss through the insulation from the heat loss of the uninsulated surface, and then dividing the difference by the heat loss of the uninsulated surface, or:

$$\text{Insulation efficiency, per cent} = \frac{C_u - C_i}{C_u}$$

where  $C_u$  = loss, Btu/hr from the uninsulated surface or pipe

$C_i$  = loss/hr as insulated

**Example:** 85 % magnesia,  $1\frac{1}{2}$  in. thick, on a 4-in. pipe with a temperature differential of 300°F, is found to have a heat loss of 0.371; the same 4-in. pipe bare, a loss of 3.29. Thus

$$\text{Insulation efficiency} = \frac{3.29 - 0.371}{3.29} \text{ or } 88.6 \text{ per cent}$$

**Insulation of High-temperature Pipes.** In insulating pipes carrying very high temperatures, it is customary to use a combination of insulations; an inner layer of high heat resistance, and an outer layer of high insulating value but lower heat resistance. Because the inner layer is usually the more expensive, only sufficient thickness should be used to bring its outer surface to a temperature permissible for the outer insulation. The final insulation efficiency is then made up by the thickness of the outer layer. Efficiencies at recommended thicknesses range from 93 to 97 per cent for moderate sizes of pipe to about 98 per cent for 18- to 30-in. pipe sizes.

**Table 20-13. Sources and Characteristics of Common Insulating Materials**

Trade name	Source of material	Method of manufacture	General insulation effect ( $k$ ) <sup>a</sup>	Fireproof	Vermine-proof
Mineral wool, rock wool, slag wool	Slag, rock, cinders or other siliceous material	Molten material is sprayed at high speed with steam to draw fibers of minute diameter	0 27-0 33	Yes	Yes
Glass wool	Special grade of glass	Same as mineral wool	0 24-0 27	Yes	Yes
Vermiculite (expanded mica)	Micaceous minerals	Calcinated to expand the rock to a fluffy mass some 16 times the original volume	0 32-0 48	Yes	Yes
Kapok.....	A silky fiber from the silk cotton tree of the West Indies	Fiber obtained from the bolls of the tree in natural form	0 23-0.24	Must be treated	Must be treated
Cork	From a species of oak tree native to Spain and Portugal	Obtained in natural form from the bark of the tree	0.30-0 32	Chars at 250°F, ignites only on contact with flame	Must be treated
Asbestos....	A variety of mineral rock or amphibole	Fibers of rock are readily separated into form known to trade	0 28	Yes	Yes
Diatomite, diatomaceous earth, infusorial earth, kieselguhr	Agglomerated shelly remains accumulated at the bottoms of ancient lakes	Used in either natural or calcined form	Various	Yes	Yes

<sup>a</sup>  $k$ , conductivity = Btu transmitted per hour per square foot material area per degree difference in temperature per inch of insulation thickness. The lower the factor the better the insulation.

Table 20-14. Physical and Thermal Characteristics of Insulating Materials<sup>1</sup>

Material	Commercial forms	Upper temp limit, deg F	Density, lb/cu ft	Thermal conductivity, Btu/hr/sq ft/deg F/in. thick at:									
				100° F	200° F	300° F	400° F	500° F	600° F	800° F	1000° F	1200° F	1500° F
Aluminum foil	Built-up, sectional, block	1000	0.2	0.28	0.37	0.39	0.46	0.52	0.58				
Asbestos	Loose fiber	800	36	0.16	1.23	1.40	1.45	1.48	1.50	1.56			
Asbestos finishing cements	Loose, dry	1000	48-60	..	1.50								
Asbestos air cell	Sectional and block; 8 plies/in.	300	12	0.53	0.65	0.77	0.89						
Asbestos felts (sponge felt)	4 plies/in.	300	19	0.48	0.56	0.63	0.71						
	Sectional and block; 40 laminations/in.	700	30	0.40	0.44	0.49	0.53	0.59					
Asbestos millboard	20 laminations/in.	700	20	0.55	0.61	0.67	0.73	0.79					
Asbestos, sprayed	Sheets	1000	54	0.90	0.95	1.00	1.20	1.40	1.50				
Concrete	Loose fiber and binder	800	7	0.36	0.41	0.46	0.53	0.63					
Insulating type	Loose granular	1800	31	1.72	1.80	1.87	1.94	2.01	2.08	2.23	2.37	2.51	2.73
Insulating refractory	Powder	2200	65	..	..	2.78	2.82	2.86	2.92	2.98	3.09	3.20	3.44
Cork	Sectional and block	200	11	0.30	0.41	0.44	0.48	0.51	0.55	0.62	0.69	0.76	0.86
Diatomaceous earth	Fine powder	1600	15	0.38	0.48	0.52	0.53	0.59	0.62	0.70	0.77	0.84	0.95
	Coarse powder	1600	22	0.45									
High-temp alumina and diatomaceous silica mixtures	Sectional and block			0.59	0.61	0.64	0.68	0.70	0.76	0.82	0.88		
Hair felt	Blanket	2000	24-30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Silica brick	Brick	3300	13	6.20	6.50	6.80	7.00	7.30	7.60	8.20	8.80	9.40	10.20
Firebrick	Brick	3200	130-150	5.80	6.00	6.20	6.50	6.70	6.90	7.40	7.80	8.30	9.00
Red brick	Brick	3000	110-112	4.50	4.70	5.00	5.20	5.50	5.80	6.30	6.80	7.30	8.10
Insulating brick	Brick	1000	100-120	4.50	4.70	5.00	5.20	5.50	5.80	6.30	6.80	7.30	8.10
	Brick	2500	39-53	..	1.57	1.73	1.84	2.01	2.14	2.50	2.53	2.83	
	Brick	2000	28-38	..	1.12	1.15	1.19	1.23	1.27	1.37	1.48	1.62	
	Brick	1600	30	..	0.78	0.81	0.85	0.89	0.93	1.00	1.09	1.16	
Magnesia 85 %	Sectional and block	600	17	0.43	0.51	0.55	0.60	0.66					
Magnesia cements	Loose, dry	600	21	0.48	0.54	0.60	0.66						
Mineral wools:	Untreated:												
Glass wool	Loose, flexible, blanket	1000	3	0.26	0.32	0.41	0.61						
	Loose, flexible, blanket	1000	4	0.24	0.30	0.38	0.52						
	Loose, flexible, blanket	1000	8	0.22	0.29	0.30	0.36						
Rock wool	Loose, flexible, blanket	1000	5	0.29	0.37	0.47	0.64						
	Loose, flexible, blanket	1000	10	0.28	0.33	0.39	0.46						
	Loose, flexible, blanket	1000	15	0.29	0.35	0.40	0.47						
Mineral-wool cement	Loose, flexible, blanket	1000	20	0.31	0.38	0.43	0.49						
Mineral-wool (waterproof)	Loose, dry	1500	24-30	0.37	0.61	0.66	0.77	0.88	1.02	1.15	1.14		
	Blanket	600	18	0.30									
	Blanket	225	18	0.36									
	Blanket	225	16	0.39									
Vermiculite	Loose, sectional, block	1600	17	0.57	0.64	0.69	0.73	0.76	0.80	0.89	0.98		

<sup>1</sup> From "Hauck Industrial Combustion Data," p. 109, Hauck Mfg Co., Brooklyn, 1944.

Table 20-15. Characteristics of Typical Insulations for Hot Pipes

Insulation	Description	Characteristics	Max temp, deg F	Typical conductivity, Btu/hr/sq ft/deg F/in. thick	Weight/cu ft
Processed silica and asbestos...	Calcined diatomaceous silica blended with asbestos fiber	High heat resistance and good insulating value. Usually used in combination with other materials	2000	@ 200°F, 0.59 @ 500°F, 0.68 @ 800°F, 0.76 @ 1000°F, 0.82	24-30
Asbestos felt (molded)....	Molded from felted asbestos fiber	Used where insulation must stand vibration or motion	1000	@ 200°F, 0.39 @ 800°F, 0.55	20
Asbestos pipe blankets	Asbestos cloth filled with asbestos fiber and quilted	For pipes and fittings where frequent removal of insulation is necessary	950		
Asbestos sponge felted	Made of asbestos fiber felts combined to give a spongy laminated material	Withstands rough use, can be removed and reapplied without loss of efficiency. Not affected by wetting and redry	700	a. 40 laminations/in.: @ 100°F, 0.40; @ 500°F, 0.59 b. 20 laminations/in.: @ 100°F, 0.55; @ 500°F, 0.79	30 20
85 % magnesia.....	85 % basic carbonate of magnesia bonded with asbestos fiber	High insulating value, light weight, one of the most efficient commercial insulations	600	@ 100°F, 0.43 @ 300°F, 0.51 @ 400°F, 0.55	17
Preshrunk asbestos felts....	Plain and corrugated asbestos felts	For low-temperature lines. Thicknesses available in multiples of 1/4 to 3/4 in.	300	@ 100°F, 0.41 @ 200°F, 0.63	0.50/sq ft (approx)
Preshrunk wool felts.....	Wool felt indented to reduce conductivity	Principally used for hot- and cold-water lines	225	@ 100°F, 0.30	13



Table 20-16. Characteristics of Flexible Insulating Materials

Insulation	Description	Typical uses	Max temp, deg F	Typical sizes	Approx weight/sq ft
High-temperature mineral-wool blankets	Mineral wool felted between various metal binders with variety of surfaces, as asbestos	Flexible insulation for baking ovens, dryers, breechings, exhaust pipes, etc.	1000	1 to 6 in. thick, 24 to 96 in. wide	1-1½ lb for 1 in. thick
Asbestos roll felt . . .	Soft felt of asbestos fiber	Suitable for wrapping around pipes and other heated surfaces	1000	½ and ¾ in. thick; 36 in. wide; 100-ft rolls	½ in., 0.59 lb; ¾ in., 1.20 lb
Asbestos blankets. . .	Asbestos cloth filled with asbestos fiber and quilted	Used for irregular surfaces, as steam turbines where removable insulation is desired	950	1½, 2, 2½ in. thick, single; 3, 4, 4½ in. thick, double	
Asbestos roll felt. . . . .	Plain and corrugated asbestos felt in flexible rolls	Covering heater pipes, warm air ducts, etc. Use at least 2 thick	300	In units of ¼ and ½ in. thick. 36-in. rolls = 125 or 250 sq ft	0.20
Asbestos roll board . . . . .	Heavy asbestos paper	Same as asbestos paper where increased thickness is desired, as fire retardant, gaskets, etc.		¾ and 1½ in. thick. 18 and 36 in. wide 50- and 100-lb rolls	¾, 0.48 lb; 1½, 0.64 lb
Asbestos paper . . . . .	Protection against heat, fire retardant. cell diaphragms (special log fiber), dielectric in electric equipment subject to heat, welding paper to protect parts against heat, etc.	Special uses include electrolytic cell diaphragms (special log fiber), dielectric in electric equipment subject to heat, welding paper to protect parts against heat, etc.		0.015 to ¾ in. thick; 18, 24, and 36 in wide; 50- and 100-lb rolls	0.015, 0.06 lb; 0.0625, 0.32 lb
Hair felt . . . . .	Made from cattle hair	Refrigerator-car insulation, cold-water fittings. For low and moderate temp only	200	¼ to 2 in thick in ¼-in. increments. 3, 4½, 6, and 9 ft wide	11 oz/sq ft at 1 in. thick

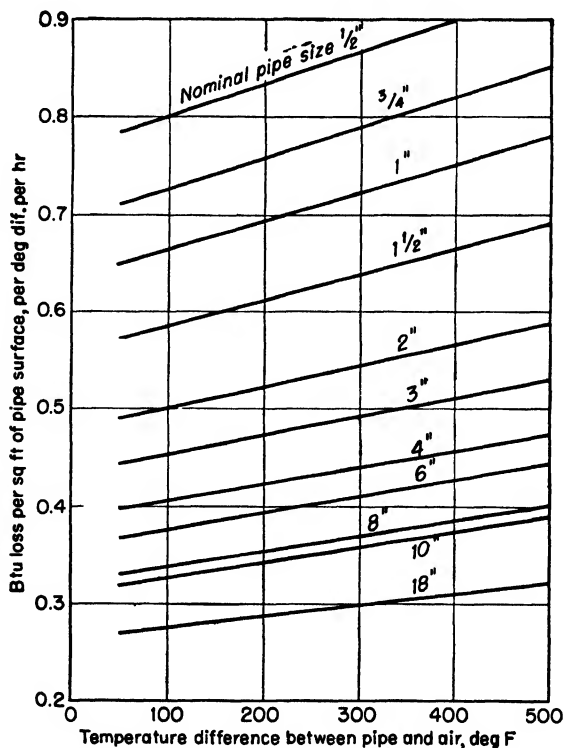
Table 20-17. Characteristics of Brick, Block, and Sheet Insulators

Material	Description	Typical uses	Max temp, deg F	Typical sizes	Weight, lb/board ft
Diatomaceous blocks (or bricks)	Made from diatomaceous earth either natural or calcined. Available for various temps	Behind firebrick linings on all types of high-temperature equipment	1600 <sup>a</sup> 2200 2500	Various	1½ to 2½ lb/brick of standard size
Refractory firebricks (insulating type) also blocks	Refractory clay and organic filler, molded, fired, and ground to size	Insulating refractories behind firebrick, stack linings, etc. Various firings	2000 2300 2600	Various Various Various	2.1 lb/brick 2.5 lb/brick 2.8 lb/brick
Sheets and blocks: Asbestos sponge felt	Asbestos fiber felts combined for spongy laminations	Withstands rough use. Not affected by wetting and drying	700	¼ to 4 in. thick	2½ lb
Asbestos felt, molded	Molded from felted asbestos fiber	Used where insulation must withstand vibration or motion	1000	.. .. .	3 3 lb
Asbestos felts, laminated	Built up of layers of plain and corrugated asbestos felt	Medium- and low-temperature boilers, warm-air ducts	300	½ to 4 in. thick in 4 to 6 ply/in.	4 ply, 1 lb; 6 ply, 1.3 lb
85 % magnesia blocks and lagging	Carbonate of magnesia bonded with asbestos fiber	High insulating value, light weight, efficient	600	½ to 4 in. thick	17 lb/cu ft
Processed mineral wool sheets, lagging, and disks	Mineral wool with waterproof binder	Refrigerating equipment, etc.	100-150	1 to 4 in. thick	1¼ lb, 1 in. thick

<sup>a</sup> Natural, others calcined.

**Table 20-18. Recommended Thickness of Various Pipe Insulations**  
(In inches)

Condition	Temp, deg F	Asbestos blankets	Asbestos sponge felted			85 % magnesia <sup>a</sup>		
			Pipes larger than 4 in.	Pipes 2 to 4 in.	Pipes smaller than 2 in.	Pipes larger than 4 in.	Pipes 2 to 4 in.	Pipes smaller than 2 in.
Hot water.....	To 212	.....	1	1	1	Standard	Standard	Standard
Steam, 0-25 lb. . .	212-266	1½	1	1	1	Standard	Standard	Standard
Steam, 25-100 lb. .	267-337	1½	1½	1	1	1½	Standard	Standard
Steam, 100-200 lb	338-387	2	2	1½	1	2	1½	Standard
Steam, low superheat	388-499	2½	2½	2	1½	Double standard	2	1½
Steam, superheat.	500-599	3 (2-1½)	3	2½	2	3	Double standard	2
Steam, high superheat	600-700	4 (2-2) <sup>b</sup>	3½	3	2			
Steam, high superheat	700-950	4½ (2½, 2)						
Max temp recommended for insulation, deg F .....		950	700			600		

<sup>a</sup> On outdoor lines an extra ½-in. of thickness is usually applied.<sup>b</sup> Asbestos blankets 4-in. thick recommended to 800°F.**FIG. 20-10.** Heat loss of pipes insulated with 85 per cent magnesia covering. (Standard thickness.) **NOTE:** Total loss in Btu/hr = factor from figure × area of pipe × degrees difference in temperature.

**Table 20-19. Surface Area of Standard Pipe**  
 (Table for converting square feet of pipe surface area to linear feet)

Nominal pipe size, in.	Sq ft surface/ lin ft	Nominal pipe size, in.	Sq ft surface/ lin ft
$\frac{1}{2}$	0.220	7	1.996
$\frac{3}{4}$	0.275	8	2.257
1	0.344	9	2.519
$1\frac{1}{4}$	0.435	10	2.817
$1\frac{1}{2}$	0.498	11	3.073
2	0.622	12	3.338
$2\frac{1}{2}$	0.753	14 OD	3.663
3	0.917	16 OD	4.188
$3\frac{1}{2}$	1.047	18 OD	4.716
4	1.178	20 OD	5.235
$4\frac{1}{2}$	1.309	24 OD	6.286
5	1.456	30 OD	7.854
6	1.734		

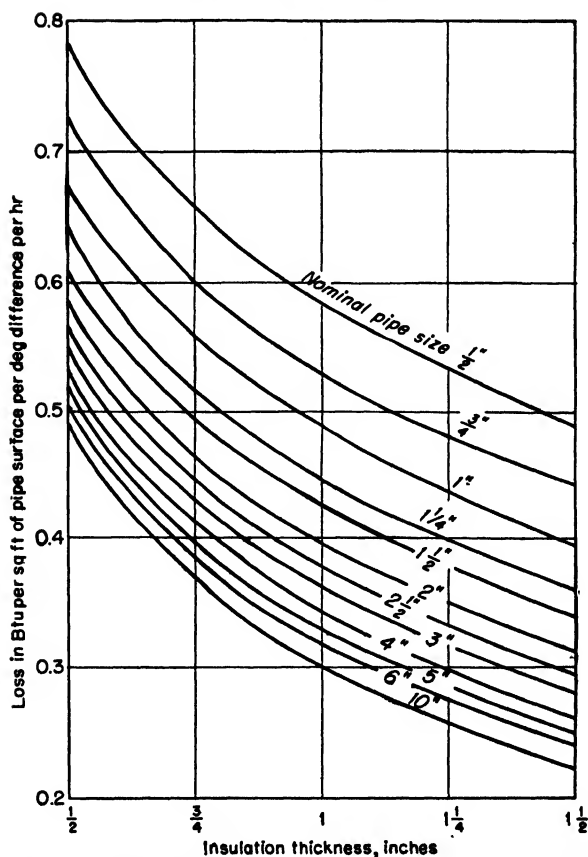


FIG. 20-11. Heat loss from pipes insulated with preshrunk wool felt.

**Insulating Cements.** Insulating cements are available in about the same temperature and physical ranges as the insulation proper. It is important to select a cement with the proper characteristics to provide comparable insulation and avoid cracking, shrinkage, and disintegration. Both insulating and finishing types are offered. Covering capacity, 1 in. thick, range from 15 to 78 sq ft per 100 lb, further emphasizing the importance of using a proper type. As manufacturers usually have or recommend a cement to correspond to each type of insulation sold, it is usually sufficient to specify cement by the name of the insulation to be used.

**Insulation of Fittings, Valves, and Special Lines.** In terms of equivalent lengths of straight pipe the radiation from standard flanged fittings to 8 in. nominal size

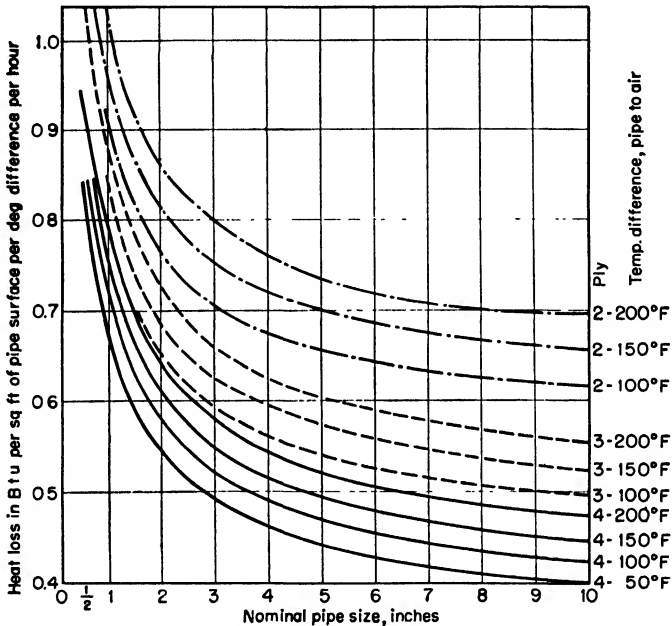


FIG. 20-12. Heat losses from lines insulated from corrugated asbestos felts. NOTE: Select curve from righthand column according to ply (2, 3, 4) of insulation and temperature difference between pipe and air.

averages about as follows: flanged couplings, 1 ft; 90-deg ells,  $2\frac{1}{2}$  ft; long-radius ells,  $3\frac{1}{4}$  ft; tees, 4 ft; and crosses,  $5\frac{1}{2}$  ft. Extra-heavy flanged fittings will average about 35 per cent higher. Pipes above 8 in. will also be higher up to a considerable amount as the larger sizes are reached. However, these values are close enough for most ordinary work at relatively low temperatures.

Where it is desired to **insulate fittings**, several types of covering are available, such as permanent with insulating blocks, removable-block insulation, and asbestos-cement insulation. The latter is usually restricted to small fittings and valves.

**Valves** are usually insulated with blankets since the usual necessity for the periodic removal of their insulation makes the blanket type far more economical than the molded insulations.

**For hot oil, tar, and similar lines** in which the temperature must be maintained to assure proper flow, the use of a parallel steam line enclosed with the main pipe in

85% magnesia will afford fireproof insulation. On outdoor lines a weatherproof jacket should be added.

**Exhaust Pipes, Incinerator Flues, Etc.** A high-temperature insulation should be applied over a metal lath so placed as to leave an air space to prevent overheating the pipe. The  $1\frac{1}{2}$  in. or more of insulation should be wired in place and well covered with several coats of cement on wire.

### INSULATING BRICKS

Insulating bricks, designed for various temperatures to a maximum of about 2600°F, are used behind firebrick linings in boilers, stills, heat-reacting furnaces, kilns, lehrs, flues, retorts, stacks, and all other types of high-temperature equipment.

In preventing heat loss, this type of brick is usually from  $1\frac{1}{2}$  to 4 times as effective as firebrick. Thus with firebrick for interior strength and resistance to the full

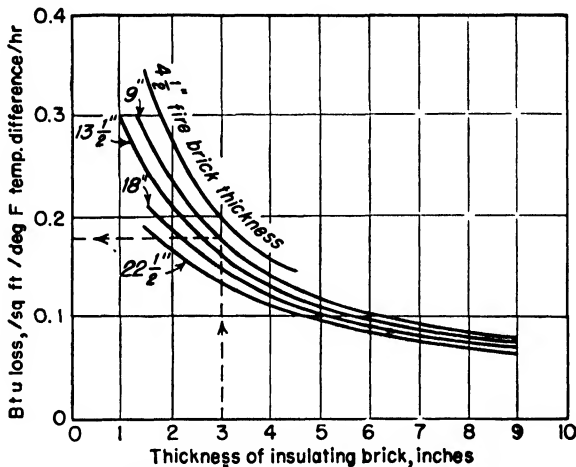


FIG. 20-13. Heat loss through insulated firebrick walls of various thickness. Example: Figures on curves show thickness of firebrick, those at bottom of table show thickness of insulating brick or block. Thus with 3 in. of insulating block and 9 in. of firebrick (total thickness 12 in.), the loss would be 0.180 Btu per degree temperature difference per sq ft per hour in still air. This is as shown in the dotted lines. NOTE: This table was calculated for 1800°F furnace temperatures. Each 100°F above or below this figure makes about a  $1\frac{1}{2}$  per cent difference in the heat-loss factors. Insulating block is assumed to be calcined diatomaceous silica combined with asbestos fiber. Insulating values of this material used alone are shown elsewhere in this chapter.

furnace heat, a backing of insulating brick gives the same or better results with materially thinner walls.

In addition to such uses, insulating brick are often used as the outside course in the combustion zone and first pass of water-tube boilers. They are also used as combination insulating and face brick on the outside of bake ovens, etc.

While air spaces have been used, in the impression that they will take the place of insulating brick, the U.S. Bureau of Mines has pointed out that a solid wall of any ordinary material is preferable to a hollow wall of the same thickness, particularly if the air space is near the furnace side. While air is a poor conductor, heat passes through it rapidly by radiation and by the convection currents set up. It is well to fill such spaces, with insulating material if possible, but, if not, with even sand, since the latter offers a higher resistance under high-temperature conditions than air.

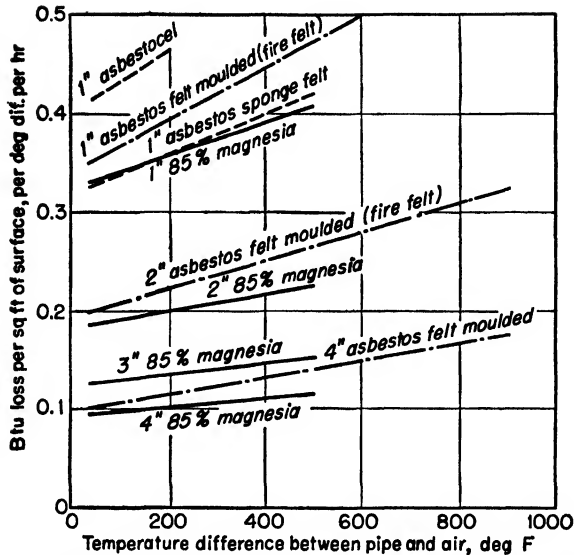


FIG. 20-14. Heat losses through various sheet and block insulations. NOTE: Total loss in Btu/hr = factor from figure  $\times$  area of pipe  $\times$  degrees difference in temperature.

### INSULATION FOR LOW TEMPERATURES

The selection and application of low-temperature insulation of any type involves more care than is common with insulation against heated surfaces. With low temperatures, the insulation must not only be permanently waterproofed but must also be sealed against the infiltration of moist air which in time would condense and destroy its insulating value.

**Important factors in the selection** of low-temperature insulation include:

1. Retention of low conductivity at low service temperatures
2. Nonabsorption of moisture and odor
3. Possibility of thorough sealing against penetration of air
4. Immunity to termites, vermin, and mold
5. Structural strength to permit handling and applying without breakage
6. Ease of sawing and working on the job

**Cement for Low Temperatures.** While portland cement may be used with such insulation, asphalt has the distinct advantages of providing waterproof construction and of setting much more quickly.

**Insulation to Retard Freezing.** No insulation, no matter how thick or efficient it may be, will prevent freezing where there is no circulation, or an inadequate amount of circulation, in the pipes, if the outside temperature remains below the freezing point for a sufficient length of time.

Insulation will retard freezing; and, if there is a certain amount of circulation, or even without circulation, if the air remains at a low temperature for a short enough period, freezing may be prevented.

To assist in quick estimates as to results which may be accomplished in retarding freezing, figures are given in Fig. 20-15 showing the length of time necessary for water in a pipe to be cooled 10°F from 42 to 32°F, with a difference in temperature between water and air of 60°F, which would correspond to an air temperature of about 20°F below zero.

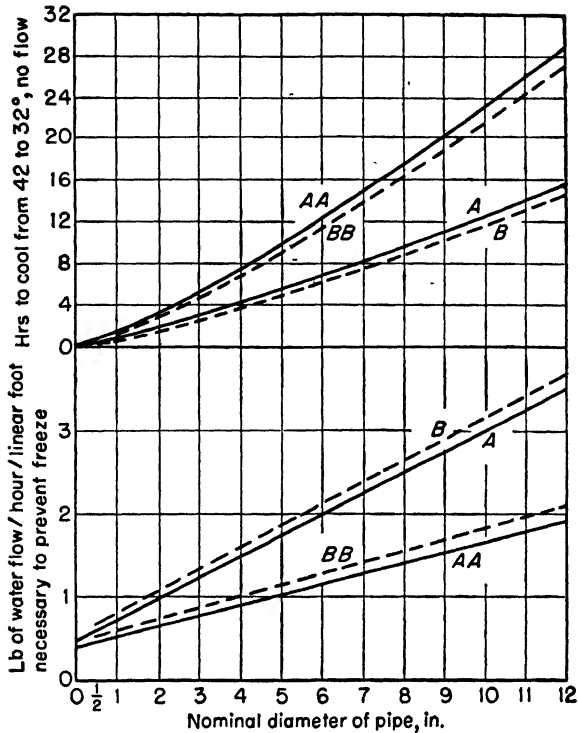


FIG. 20-15. The freezing of water in pipes with various insulations. *A* = 2 in. of hair-felt insulation; *AA* = 4 in. of hair-felt insulation; *B* = 2 in. waterproofed mineral-wool insulation; *BB* = 4 in. waterproofed mineral-wool insulation. NOTE: Figures based on 60° temperature difference. Weights of water are per lineal foot of line; minimum flows shown must be multiplied by length of exposed line to obtain total necessary flow.

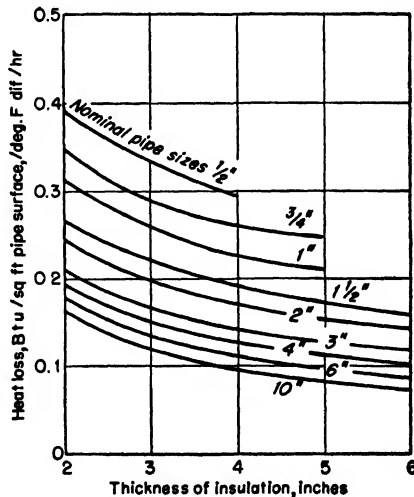


FIG. 20-16. Heat loss from pipes insulated with built-up hair felt. (Low temperature insulation.)



Water should not be allowed to remain stationary for longer than one-half the time shown in Fig. 20-15, which indicates the minimum amount of water which should be supplied per hour at 42°F water temperature in order to prevent the temperature of the water from being lowered to the freezing point. The weight as obtained from this figure should be multiplied by the length of the pipe in feet. In order to provide against temporary reduction in flow due to lowered pressures, etc., a factor of safety of at least 2 should be allowed. If the water enters the pipe at 52°F, instead of 42°F, it will take double the time given in order to cool it to the freezing point, or, conversely, only half as much water need be circulated. On the other hand, if water

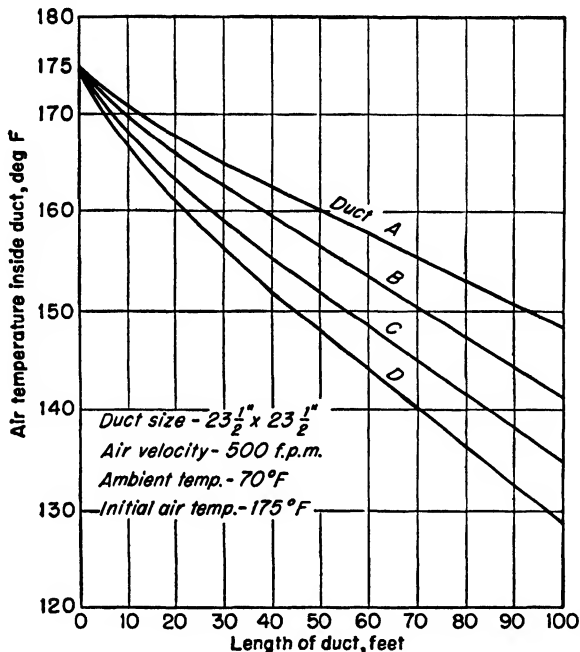


FIG. 20-17. Inside-air temperature drop for metal ducts with various outer surfaces. Duct A = duct covered with  $\frac{1}{4}$  in.-corrugated asbestos; B = aged aluminum duct bare; C = aged galvanized duct; D = duct covered with asbestos paper. ("Kaiser Aluminum," Permanente Products Co., Oakland, Cal.)

enters at 34°F, it will be cooled to 32°F in one-fifth of the time given, or five times the water will be required.

If the minimum atmospheric temperature is about zero instead of the calculated -20°F below zero (temperature difference of about 40°F between water and air), the time required to cool water to the freezing point will be 60/40 times that given in the table, or the amount of flow required will be 40/60 that of the table.

Where water must remain stationary longer than the safe length of time indicated, the only sure way to protect the line is to provide a small steam or hot-water line alongside the water line and then place insulation around both lines.

#### Heat Losses from Low-temperature Metal Air Ducts

Heat losses from low-temperature warm-air ducts are the resultant of a combination of convection and radiation losses. With surrounding conditions and surface temperatures the same, convection losses will depend on outside air currents, but

radiation losses are affected by the emissivity of the duct material. Thus heat losses may be minimized in two ways:

1. By applying insulating materials thick enough to reduce surface temperatures. With low surface temperatures, radiation and convection losses are negligible even though the surface has high emissivity.

2. By constructing the ducts of a material of low emissivity, such as aluminum, which will reduce radiation losses even though surface temperatures are high.

According to Permanente Products Co., Fig. 20-17 was calculated from basic data as published in the *Transactions of ASHVE*, to show typical losses from ducts having various covered and uncovered surfaces.

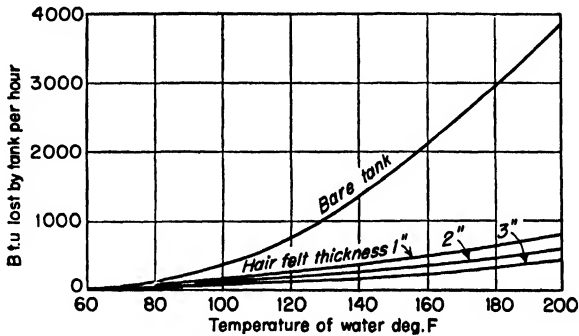


FIG. 20-18. Heat loss from 30-gal tank, uninsulated and insulated. (Assuming 68°F room temperature.)

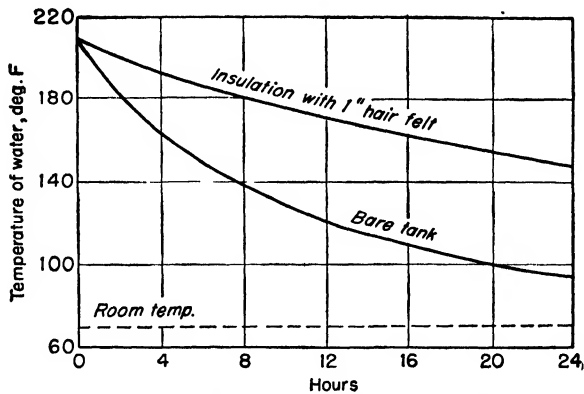


FIG. 20-19. Cooling rate of 30-gal tank, uninsulated and insulated. (Tank 12 in. diameter, 60 in. long.)

## INSULATION OF HOT-WATER TANKS

Adequate insulation of hot-water tanks is important not only from a standpoint of saving fuel, but also to retard the cooling of the tank when heat is not being supplied. The latter tends to equalize the temperature of the water in the tank at all times. Figures 20-18 and 20-19 show the Btu loss and cooling effect of an insulated and uninsulated 30-gal tank. The losses from larger tanks would be proportionately greater.

### ANTISWEAT PIPE INSULATION

While any effective low-temperature sealed pipe insulation will retard condensation and damage from dripping, several have been designed with this purpose specifically in view.

A typical insulation of this type is made of preshrunk insulating felts and waterproofing felts. The waterproofing felts, on the inner and outer surfaces of each layer, protect the insulation from the infiltration of moisture. The material is applied with all joints staggered.

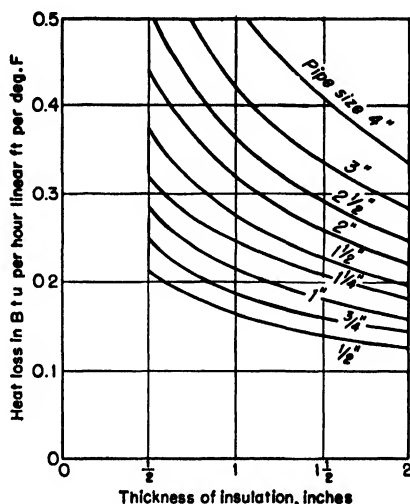


FIG. 20-20. Heat loss with antisweat waterproofing felts.

The proper thickness of such material depends on the temperature and humidity of surrounding air in relation to the temperature of the pipe. On pipes with temperatures over 50°F, 1 in. is usually used if the relative humidity is less than 75 per cent; 1 1/2-in. if the humidity is between 75 and 80 per cent. For temperature between 32 and 50°F, if relative humidity is under 75 per cent the 1 1/2 in. thickness is used.

All joints and cracks must be carefully sealed for effective results.

## CHAPTER 21

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### BOILERS AND STEAM GENERATORS

<b>Definitions and Terms</b> .....	704
ASME Boiler Construction Code.	
<b>Fundamentals of Boiler Design</b> .....	706
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## DEFINITIONS AND TERMS

**Load, Capacity, and Rating.**<sup>1</sup> The load of a steam-generating unit at any time is the actual rate of heat absorption or delivery of steam at that time and is therefore expressed in the same units as capacity. Thus the maximum load that can be carried becomes the "capacity," and the use of pounds of steam per hour to express the various loads carried during a series of tests is satisfactory if the pressures and temperatures of the steam and feed water have been held constant, or nearly so, during each test.

When boilers consisted of simple convecting surfaces, a number of empirical terms were used to express the capabilities of the unit. These terms were not satisfactory, since they did not precisely define the true output of the unit in the same fashion that the output of a turbine is defined by the term mechanical horsepower. While these terms are obsolete, they are still in use, particularly with small boilers, since it takes time to make changes, and the material is still firmly entrenched in the trade literature and catalogues.

**Boiler Horsepower.**<sup>2</sup> The empirical term, a **boiler horsepower**, is defined as the equivalent of evaporating 34.5 lb water from and at 212°F per hr. Expressed in Btu, this equivalent evaporation amounts to 33,472 Btu per hr.

**Horsepower.** One horsepower is defined as 10 sq ft of boiler heating surface. Heating surface was further defined as that which is gas-swept on one side, and simultaneously water-touched on the other.

To have the two definitions consistent, the heating surface should absorb energy at the rate of 33,472/10 or 3,347.2 Btu/hr/sq ft, or the so-called normal rating.

The ASME Power Test Code suggests:

The rating of boilers for size only, in square feet of heating surface, should be adopted. The area method has been in use for years in Europe, and in view of the fact that the ultimate steaming capacity per square foot is dependent on the amount of fuel fired, it is a suitable unit, as not involving capacity.

**Per Cent Rating.** In the past, the term per cent of rating found active application in practice and is still used by some. Rated capacity, normal rating, and 100 per cent rating were used interchangeably to mean the same thing.

$$\text{Per cent rating} = 1,000 \times \frac{H_s}{A_{hs}(33,472)}$$

where  $H_s$  = heat input to the steam, Btu/hr

$A_{hs}$  = heating surface, sq ft

One boiler horsepower = 33,472 Btu per hr. In general, it is applied to installations in which the only heating surface is the boiler.

Under the old definitions, the convection surface, which is now only a small part of the modern unit, is the **boiler**. The modern unit is complex and consists of furnace and boiler evaporative surface, superheater, economizer, and air heater and can be more accurately defined by the term **steam generator**. Therefore, the combined performance of all these steam-generator elements cannot be expressed in either boiler horsepower or equivalent evaporation. The capacity may be expressed in terms of either:

1. Actual steam generated in pounds per hour, at a specified temperature and pressure and from feed water at a definite temperature.

<sup>1</sup> BARNARD, WILLIAM N., FRANK O. ELLENWOOD, CLARENCE F. HIRSHFELD, "Elements of Heat Power Engineering," 3d ed., pp. 437, 666, 665-742, John Wiley & Sons, Inc., New York, 1933.

<sup>2</sup> DE LORENZI, OTTO, "Combustion Engineering," pp. 14.1-18.44, Combustion Engineering-Superheater, Inc., New York, 1947.

2. The rate of heat absorption of the unit in Btu per hour, which is the more exact method of expressing capacity. In this manner, variations of pressure, steam temperature, and feed-water temperature are accounted for.

The *Standards Committee of the ASME* has suggested that:

The Btu is the approved unit in which to express the rate of heat absorption of a boiler or its output per hour. The statement of output or performance in Btu per hour is basic and convenient. Frequently, however, it will be more convenient to use multiples of the Btu as a unit of measure. At such times the symbols **kB = 1,000 Btu** and **mB = 1,000,000 Btu** are recommended in lieu of names for these multiple units.

These terms have not been adopted by engineers for general use.

**Measurement of Heat-absorbing Surfaces.** The modern steam-generating unit consists of a number of different types of heat absorbing surfaces. In the *ASME Test Code for Stationary Steam Generating Units* is given the following definition of what constitutes heating surfaces:

The steam-generating unit heating surface shall consist of that portion of the surface of the heat-transfer apparatus exposed on one side to the gas or refractory being cooled, and on the other to the fluid being heated, measured on the side receiving heat.

In the case of water walls, the *ASME Test Code for Stationary Steam Generating Units* defines this heating surface as follows:

Heating surface in the furnace or furnace boundaries shall be measured as follows:

A. Tubes wholly exposed or wholly or partly embedded in refractory—that portion of the surface of the tubes which is exposed to the gas or refractory being cooled.

B. Tubes provided with extended surface—that portion of the surface of the tube and extensions which is exposed to the gas being cooled.

C. Tubes protected by blocks rigidly attached to the fire faces—that portion of the surface of the blocks which is exposed to the gas being cooled.

The foregoing definitions are useful in standardizing surface specification. They are of little value, however, to the design engineer attempting to determine heat absorption. To arrive at this value, it is necessary to use effectiveness factors to correct the total surfaces for various degrees of heat absorption. These factors are based on data gained from many installations operating with a wide range of fuels, under differing load conditions. Such experience factors are of great value to those who fully understand their application and who are well aware of their limitations.

**ASME Boiler Construction Code.** Substantially most power-boiler manufacturers of stationary service types fabricate their units according to the *Rules of the Boiler Construction Code of the ASME*. This pertains to specifications for materials used, as well as details of **construction** of both the water-tube and fire-tube types.

Since all the states of the United States have not adopted the code, it is recommended that the engineer, in purchasing a boiler, see that it conforms to the code and is so stamped.

The National Bureau of Casualty and Surety Underwriters, Boiler and Machinery Division, New York, issues at frequent intervals a *Synopsis of Boiler Laws, Rules and Regulations, by States, Provinces, and Cities (United States and Canada)*. This synopsis will be found very valuable in obtaining the requirements of the various cities and states, for boiler construction, installation, inspections, certificates, fees, etc. If a boiler is to be installed in an area that has its own boiler rules, these should be carefully reviewed to be sure that the boiler fully complies with all regulations.

**Identification.** Illustrated in Fig. 21-1 are the symbols used by the ASME for identification.

**Location of Stamps.** The location of stamps, according to the ASME Code, shall be as follows:

1. Horizontal-return-tubular boilers: on the front head above the central row of tubes.
2. Horizontal-flue boilers: on the front head above the flues.
3. Traction, portable, or stationary boilers of the locomotive type or star water-tube boilers: on the furnace end above the handhold. On the traction boilers of the locomotive type: on the left wrapper sheet forward of the driving wheel.
4. Vertical fire-tube and vertical submerged-tube boilers: on the shell above the fire door and handhole opening.
5. Water-tube boilers: on a head of the steam-outlet drum near and above the manhole opening.
6. Scotch marine boilers: on the front head, above the center or right-hand furnace.

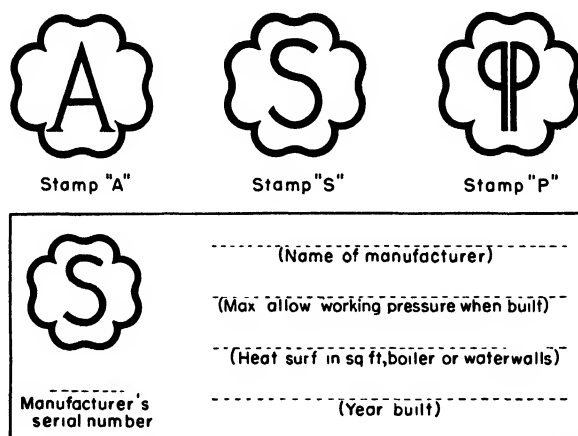


FIG. 21-1. Official American Society of Mechanical Engineers (ASME) identification symbols. Stamp "A" denotes the ASME standard for assembly; Stamp "S" denotes the general ASME standard of compliance; Stamp "P" denotes the ASME standard for welded piping.

7. Economic boilers: on the front head, above the center row of tubes.
8. On any of the above types where there is not sufficient space in the place designated, and for other types and new designs: in a conspicuous place.
9. Superheaters: on superheater header near outlet. Other headers shall carry identifying marks.
10. Economizers: at a handy location on water-inlet header or drums. Other headers shall carry identifying marks.
11. Water walls: on one end of a lower header. Other headers shall carry identifying marks.

It must be emphasized that the Power Boiler Code is applicable for construction purposes only, not for operation. Copies of the code may be obtained from the ASME.

## FUNDAMENTALS OF BOILER DESIGN

**Steam-generator Requirements.**<sup>1</sup> Because of the wide variety of possible installations and operating conditions, only the most general steam-generator requirements are given. The relative importance of these requirements is dependent on the type of service and the operating circumstances.

<sup>1</sup> BARNARD, WILLIAM N., FRANK O. ELLENWOOD, and CLARENCE F. HIRSHFELD, *op. cit.*

1. The design of the steam generator should be sufficiently adequate so that the unit will generate enough steam to meet maximum requirements of the rated load as well as enough reserve to meet emergency overload. Since the furnace shape is so important for the proper combustion of the desired fuel, the boiler form must be such as to accommodate the furnace properly. Also, the design must contain adequate space for the heat-exchanger equipment such as superheaters, economizers, preheaters, or water walls that might be required in the completed design.

2. Safety of a steam generator is primarily a problem of correct design. Materials, proportions of the boiler elements, and construction should be at least as good as those specified in the Boiler Construction Code and in the Interpretations of the Boiler Code, prepared by the ASME and frequently revised to meet changing conditions. Care should also be taken that the boilers conform to any local ordinances and the requirements of the insuring company. Not only should the pressure elements be adequately proportioned, but the possibility of high stress or damage due to expansion or contraction due to normal temperature changes or normal temperature gradients should be considered. For instance, some designs incorporate curved tubes which give a necessary degree of flexibility. Also the type of support or method of suspension should not induce serious stresses. Abnormally thick plates should not be subject to intense radiation or flame.

3. All parts of the unit must be readily accessible for maintenance and repairs. Suitable access doors must be supplied in the setting so that the interior of the furnace and the exterior heating surfaces may be readily serviced. All the interior similarly must have provision for cleaning and inspection by the use of manholes placed to facilitate these operations. All the exterior surfaces should be so arranged that any deposits of soot, fly ash, and the like are easily removed by either fixed soot blowers or lances inserted in ports in the setting. Care should be taken that repairs are possible and can be completed in the shortest time. Not only must the design of the boiler and the setting be checked, but the location in the boiler room must be scrutinized, to provide for the removal and the replacement of the tubes which usually provide the major structural difficulties.

4. The usual type of steam generator depends on natural convection for its water circulation; some types have forced circulation by pumps. Hence the paths of natural circulation should have a definite fixed pattern that is established by design and experiment. Heat must be added at the proper places that will establish this pattern. Care must be taken that there is no stagnant fluid in contact with high temperatures or that the fluid does not short-circuit.

5. The passage of the gases should be arranged to maintain the proper velocity over the heat-transfer surface. No stagnant pockets of gas should be allowed, since, within limits, the greater the velocity the greater the heat transfer. Suitable baffles are used to direct the gases.

6. Priming, the entrainment of large amounts of moisture in the steam withdrawn from the boiler, produces wet steam, whereas it is desirable to produce dry steam. Large steam-releasing areas help prevent priming; also large steam volumes help precipitate the moisture. The presence of certain impurities promote foaming which naturally increase priming. The amount of impurity present can be reduced by blowdown, either continuous or intermittent. Frequently the boiler is equipped with water-separating devices to cut down the entrained moisture.

7. Large volumes of water in the steam generator take care of load fluctuations without much change in the level of the water, and hence need less attention. The larger volumes give greater reserve in case of sudden demands than in the smaller volumes. However, in case of an explosion, greater damage results with the larger volumes.



8. Care should be exercised as to the location of the feed-water discharge into the boiler. Cold water should not come in contact with the boiler shell. Certain impurities in the feed water precipitate as they rise in temperature, and deposit as mud. This precipitation should occur where the mud will cause least damage and where it can readily be withdrawn.

9. A thorough engineering cost study should be made of the prospective steam generator. Not only should the initial cost be taken into account but other expense items—furnace and setting, type of combustion equipment, boiler auxiliaries and controls, as well as installation and transportation—should be considered. Maintenance and repairs and cost of space and building will differ with various boiler types and must be a part of the boiler study.

### CARE AND OPERATION OF POWER BOILERS<sup>1</sup>

**Preparing Boiler for Service.** Before filling a boiler for service, make certain that it is free from scale, oil, tools, and other foreign matter and that there is no one in the boiler. Manhole and handhole gaskets should be new or in good condition. Use suitable graphite paste to prevent the gaskets from sticking and to secure tightness.

**Filling Boiler.** Do not refill a boiler while it is hot. Hot water should be used if available, and the boiler should be vented to permit the air to escape, while filling. Fill to the normal working level.

**Getting Up Steam.** Ventilate the furnace thoroughly and start the fire with damper and draft doors open. Highly inflammable oils or gasoline should not be used in starting fires where solid fuel is used. Start the fire early so that steam pressure may be raised without forcing the boiler.

**Gas, Oil, or Powdered-coal Fuel.** Do not turn on the fuel supply at any time until the furnace has been thoroughly ventilated and a lighted torch properly placed to ignite the fuel instantly. If the fire goes out, the fuel supply should be shut off immediately and no attempt should be made to start the fire until the furnace has again been ventilated.

**Cutting In Boiler.** In placing a boiler on the line with others which are already in service, keep its stop valve closed until the pressure in the boiler and the steam main are approximately equal. See that the steam piping is thoroughly drained before the valve is opened. Open the valve slightly; then, if there is no unusual jar or disturbance, complete the opening slowly. Close the valve at once if there is the slightest evidence of an unusual jar or disturbance in the boiler or piping.

**Water Level.** When going on duty, determine the level of the water in the boiler. The gauge glass, gauge cocks, and connecting lines should be blown several times daily to make sure that all connections are clear and in proper working order. The gauge glass must be kept clean because it is of extreme importance that the water level be accurately indicated, and if the true level cannot be determined immediately the boiler should be removed from service and all water-level-indicating attachments checked.

**Low Water.** In case of low water, immediately cover the fuel bed with ash, fine coal, or earth. Close the ashpit doors and leave the fire doors open. If gas, oil, or powdered coal is used as fuel, shut off the supply to the burner. Do *not* turn on the feed water. Do *not* open the safety valve or tamper with it in any way. Cool the boiler, ascertain the level of water in the boiler, and correct the cause of the low-water condition.

**Safety Valves.** Each safety valve should be made to operate by steam pressure with sufficient frequency to make certain that it opens at the allowable pressure, and

<sup>1</sup> The Hartford Steam Boiler Inspection and Insurance Co., Philadelphia, Pa. Lack of space prevents the inclusion of detailed instructions for the care and operation of all types and sizes of power boilers. These "notes" apply to the type usually found in smaller industrial plants and institutions.

the plant log should be signed by the operator to indicate the date and operating pressure of each test. Each safety valve should have a try lever with which it may be tested by hand. If the pressure shown on the steam gauge exceeds the pressure at which the safety valve is supposed to blow or if there is any other evidence of inaccuracy, no attempt should be made to readjust the safety valve until the correctness of the pressure gauge has been determined.

**Blowoff Pipe.** If a continuous blowdown is not provided and particularly if the feedwater is of poor quality, the boiler should be blown down at frequent intervals to prevent serious scale accumulations. If it is necessary to blow down the water-wall headers, it should be done only when the boiler is under very light load or no load to avoid disturbing the circulation and possible overheating of the tubes. When blowing down a boiler where a valve and cock are used in the blowoff line, first open the cock and then open the valve slowly. After one gauge of water is blown down, the valve should be closed slowly before the cock is closed, to avoid water hammer. If there is only one valve, it should be opened and closed very slowly. Do not leave the boiler during the blowing-down operation.

**Feed Valve.** The boiler feed line should have two stop valves, with a check valve between, located near the connection to the boiler. The feed water should enter each stop valve under the disk so that the disk will not act as a check valve and prevent water from entering the boiler should the disk become loose from the stem.

**Foaming and Priming.** In case of foaming, reduce the furnace temperature and decrease the load on the boiler until the true water level can be determined. Maintain a normal level by alternately feeding fresh water and operating the blowoff valve. Use the surface blowdown freely, if the boiler is provided with one. Cool, empty, and clean the boiler as soon as it can be done, and investigate the condition of the feed water being used. Have a sample of water analyzed, and get recommendations for proper treatment.

**Automatic Controls.** Automatic-control devices should be kept in good operating condition at all times. A regular schedule for testing, adjustment, and repair of the controls should be adopted and rigidly followed. The emergency low-water feeder and the low-water fuel-supply cutout should be tested daily when the boiler is in service, and the testing should be done in accordance with the manufacturer's instructions.

**Banking the Fire.** Clean the fire before banking. Push the fire back against the bridge wall, and cover with coal. Clean the balance of the grate and close the ashpit and fire doors. Adjust the damper, but do not close it tightly. The damper should be arranged so that it cannot be completely closed. Before breaking the banked fire, be sure the damper is wide open and that the furnace and breeching leading to the stack have been ventilated.

**Taking Boiler Out of Service.** Stop the supply of fuel, burn out the fuel in the furnace, and cool the setting and boiler slowly. After the boiler ceases to require feed water, close the feed-water valves and the main steam stop valve. Keep the fire doors and damper open so that air will circulate through the furnace. Keep flue or smoke-box doors closed. One gauge of water at a time may be blown from the boiler and replaced with fresh water until the furnace is cool enough to permit emptying the boiler without causing damage to the boiler or setting and the pressure has been reduced to 10 lb or less. The boiler may then be emptied and the manhole and handhole plates removed.

**Avoid Scalding Men.** Attach a sign, DO NOT OPEN—MAN IN BOILER, to each valve in the steam lines, feed-water lines, and blowoff pipes connected to a boiler that is ready for cleaning and repair. Do not remove the signs or open a valve until the

boiler is closed and ready for filling. It is well to lock the main steam stop valves and blowoff valves in the closed position when the boiler being cleaned or repaired is in the same battery with other boilers under pressure. Padlocks and chains may be used for this purpose.

**Feed-water Treatment.** It is necessary that most feed water be properly treated to prevent internal corrosion, deposition of scale, and formation of sludge and in some cases to avoid caustic-embrittlement cracking. Treatment of the feed water should be based on an analysis of the water and should be frequently checked. It is desirable that the feed-water treatment be checked at regular intervals by a reputable feed-water consultant.

**Cleaning Boiler.** The frequency of boiler cleaning depends upon the quality of the feed water, the treatment used, and the kind of service to which the boiler is subjected. The scale condition should be kept under control, using mechanical means of cleaning, if necessary. The use of a large amount of chemicals in the feed water or a change in feed water is likely to cause the loosening of a considerable amount of scale; therefore, the boiler should be cleaned thoroughly within a few days after a change in feed water or treatment.

**Oil in Boiler.** Oil acts as a nonconductor of heat and should not be allowed to get into a boiler, as it may cause overheating and bulging of plates and tubes as well as leakage at seams and tube ends. Soda ash or caustic soda used in reasonable amounts will aid in the removal of the oil. Oily deposits, when discovered, should be reported to the company's inspector or the feed-water consultant for advice as to the proper means of removal.

**Fusible Plugs.** Fusible plugs, if used, should comply with any local laws that may be in effect, and they should be cleaned at each boiler washing and should be replaced with new plugs annually.

**Leakage and Repairing under Pressure.** If small leaks occur, they should be located and repaired when the boiler is removed from service. If a serious leak occurs, the boiler should be removed from service immediately for inspection and repair. No repairs of any kind should be made to a boiler or piping while the parts upon which the work is to be done are under pressure. Neglect of this precaution has resulted in many serious accidents.

**Care of Idle Boiler.** If a boiler is to be out of service for a month or more it should be emptied, opened, and cleaned internally and externally. It should then be dried out by building a small fire of paper or other light material in the furnace. Do not let the boiler get so warm as to be uncomfortable to the hand. See that no moisture can collect within or about the boiler. The manhole and handhole plates may be placed in position without tightening them. Remove and store the steam-pressure gauge and its siphon pipe, if likely to be damaged. The idle boiler which remains filled with untreated water and covered with soot may deteriorate rapidly. If necessary to keep the boiler filled, treated water should be used to prevent internal corrosion.

**Corrosion.** To prevent rapid external corrosion, do not allow moisture to come in contact with the outside of the boiler at any time. The mud drums, nipples, tube ends, and other similar parts of water-tube boilers should be kept free from soot while the boilers are idle. All parts of a boiler below the water line should be given an external examination annually.

**Preparation of Boiler for Inspection.** After the boiler has been cooled, remove the ash and flue dust from the grate and combustion chamber. Empty, open, and clean the boiler internally and externally prior to the inspection. Thorough examination of the boiler is necessary to its safety and gives protection to everyone connected with its operation.

**Local Laws and Ordinances.** The operator should understand all local laws relating to the duties of engineer and fireman and to the safety requirements of the work. A careless boiler operator is a source of danger to others as well as to himself.

### STEAM-GENERATOR TYPES

The number and variety of boilers or steam generators manufactured make it impossible to present a detailed description of all types. However, it is possible to

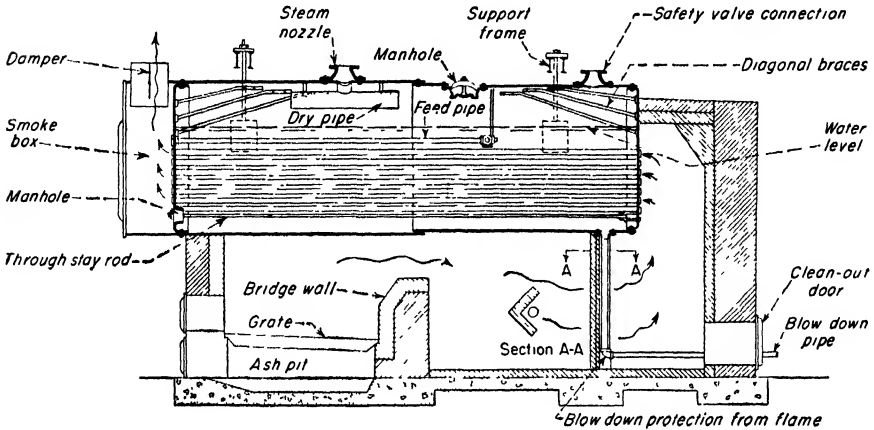


FIG. 21-2. Horizontal-return tubular boiler. The products of combustion after sweeping over the bottom of the shell pass through the tubes and out through the smoke box to the flue. Smoke box and rear of furnace have access doors. Refractories are used in the furnace and the rear of the furnace. (*Power*, December, 1946.)

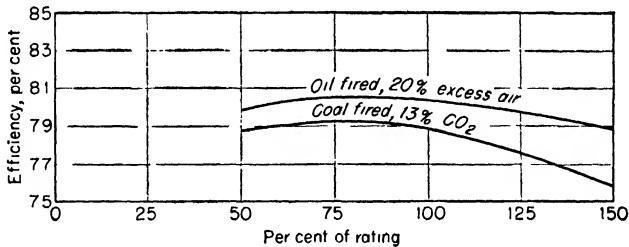


FIG. 21-3. Performance curves of horizontal-return tubular boiler. Boiler tested was  $72 \times 18 - 150$  hp, 100-psi working pressure. Coal-fired curve is based upon coal having 13,900 Btu/lb as fired. Oil-fired curve is based upon bunker C having 18,600 Btu/lb as fired.

break this broad topic into two classifications, the **fire-tube** and the **water-tube** types.

Boilers are made in a wide variety of sizes, arrangements, capacities, pressures, and applications. There are available a numbers of designs that have been used for many years so that a great deal of operating experience and improvements have been incorporated into their design and construction. Many boilers have been standardized to fit a wide range of application. Large plants and central stations are specifically designed to secure maximum effectiveness of operation and efficiency for the given conditions.

**Fire-tube and Water-tube Types.** The broadest difference in the classification of generators is as between the "fire-tube" and the "water-tube" types.

In general, the fire-tube types are designated as "boilers," i.e., they produce saturated steam only. While superheaters are sometimes fitted to these boilers, they are the exception rather than the rule. Fire-tube boilers include most of the smaller types of unit.

In contrast, water-tube units are usually complex and incorporate a number of features to leave the primary tube bank as only one part of a comprehensive steam-

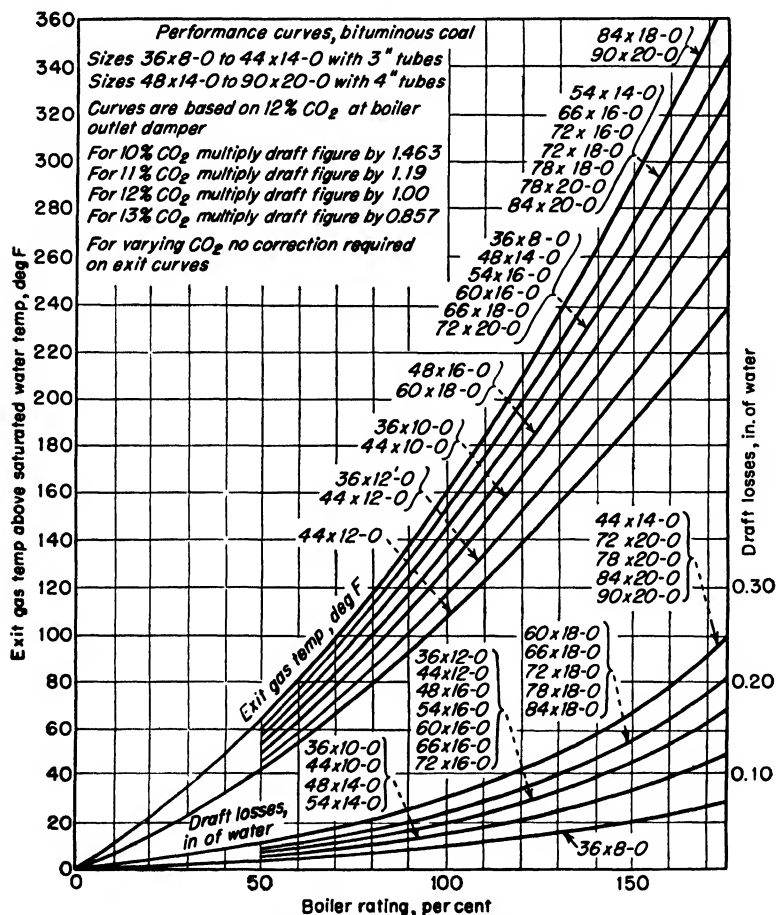


Fig. 21-4. Performance curves of horizontal-return tubular boiler.

generating system. Water-tube units are thus usually called "steam generators" rather than boilers.

### FIRE-TUBE STEAM BOILERS

**Horizontal-return Tubular (HRT).**<sup>1</sup> This is probably the most thoroughly standardized piece of equipment used in boiler work. Part of the heat-transfer surface is the bottom of the shell, which is swept by the products of combustion and which also receives some radiation from the furnace (Fig. 21-2). The gases then pass through tubes running through the shell; hence the name fire tube. Its low cost, simplicity

<sup>1</sup> Except as otherwise noted, the performance curves and typical illustrations in this section are reproduced through the courtesy of Erie City Iron Works.

of construction, its relatively large water-holding capacity, and the ease with which it can be adapted to many methods of firing have all contributed to its long-standing popularity. Within its usual ranges of sizes and pressures, it is the most widely used type of boiler. The danger of overheating limits the amount of forcing. The efficiency is relatively high with proper design. Most of these types operate under 200 psi, but units have been built for 400 psi. Shell sizes go as high as 96 in. in diameter.

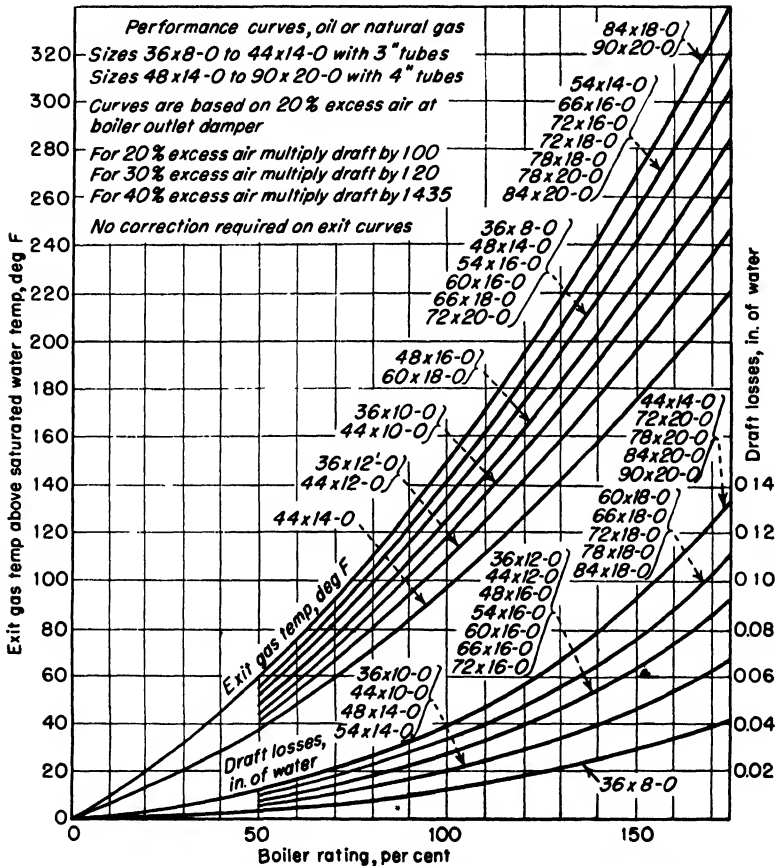


FIG. 21-5. Performance curves of horizontal-return tubular boiler.

The HRT boiler<sup>1</sup> operates well at an evaporation rate of about 5 lb of steam per sq ft of boiler heating surface per hr. They should not be forced beyond 7 lb/sq ft/hr.

The Combustion Engineering-Superheater Nuway boiler is a horizontal-return tubular boiler that has been revised in design to improve circulation and permit higher capacities than in the conventional types. The tubes are 3 in. in diameter grouped in vertical banks. Baffles are placed between the banks. The open vertical lanes, between baffle plates, provide areas through which the water is free to circulate downward, without interference, establishing a definite circulation path. The steam generated at the surface of the tubes flows upward through the banks. This upward

<sup>1</sup> DE LORENZI, OTTO, *op. cit.*

circulation is confined, by the baffles, to the space in which the tubes are located. Water is carried along with the steam to the top of the tube bank. It is then free to return to the bottom of the drum through the unobstructed lanes between the baffles. Directly below each baffle is an angle which serves to direct the downcoming flow of water to the several banks. Rapidity of circulation is thereby materially increased. The maximum rate of evaporation should not exceed 9 lb/sq ft/hr.

The general acceptance of the horizontal-return tubular boiler has been because of their many good qualities, and in spite of the drawback of their riveted construction.

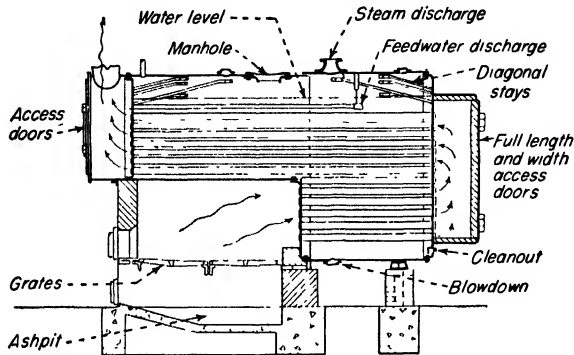


FIG. 21-6. Two-pass HRT boiler—Economic type. Furnace gases pass through the short lower tubes and then return through the longer upper tubes, out through the smoke box to the flue. Both the smoke box and the rear box have full-width access doors. Furnace and rear box are refractory-lined.

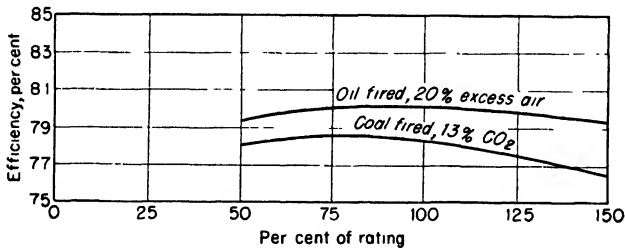


FIG. 21-7. Performance of two-pass HRT boiler—Economic. Test on a 150-hp boiler, 100-psi working pressure. All coal-fired curves are based upon coal having 13,900 Btu/lb as fired. Oil-fired curve is based upon bunker C oil having 18,000 Btu/lb as fired.

They have always been made in two (sometimes three) courses. This puts a riveted seam over the fire. Under severe conditions of service, leaks develop, and in extreme cases fire cracks form between the rivet holes and the boiler life is unduly shortened. The head seams, where the shell plates are riveted to the heads, sometimes need attention, and it is difficult to make these repairs without seriously disturbing the brickwork. These faults have been eliminated by the recent use of class 1 welding. The covering plates, called butt straps, which formed the horizontal seams have been eliminated. The flanged heads are butt-welded to the shell plates, forming one smooth continuous piece of metal.

*The "Economic" Type HRT Boiler.* The "Economic" type (Fig. 21-6) has the lower rear section formed into a half cylinder that is joined by flat plates to the upper shell. These flat plates must be stayed to prevent bulging. They are normally built for 150 psi but can be built for greater pressures. In some designs a water wall on each side of the furnace is incorporated, protecting the refractory. Another

Table 21-1. Steel Boiler Institute Ratings for Commercial Steel Boilers

Mechanically fired							Hand-fired										Tappings	
SBI rating			SBI net rating			Min furnace volume, cu ft <sup>a</sup>	Min furnace height, in. <sup>b</sup>	Min heating surface, sq ft	SBI rating			SBI net rating			Min grate area, sq ft	Steam outlet in.	Steam return I.P.S., in. <sup>c</sup>	
Sq ft steam	Sq ft water	Btu/hr	Sq ft steam	Sq ft water	Btu/hr				Sq ft steam	Sq ft water	Btu/hr	Sq ft steam	Sq ft water	Btu/hr				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	
2,190	3,500	526,000	1,800	2,880	432,000	15 7	26	129	1,800	2,880	432,000	1,500	2,400	360,000	7 9	6	3 <sup>a</sup>	
2,680	4,280	643,000	2,200	3,520	528,000	19 2	28	158	2,200	3,520	528,000	1,830	2,930	439,000	8 9	6	3 <sup>a</sup>	
3,160	5,050	758,000	2,600	4,160	624,000	22 6	29½	186	2,600	4,160	624,000	2,170	3,470	521,000	9 7	6	3 <sup>a</sup>	
3,650	5,840	876,000	3,000	4,800	720,000	26 1	29½	215	3,000	4,800	720,000	2,500	4,000	600,000	10 5	6	4 <sup>a</sup>	
4,250	6,800	1,020,000	3,500	5,600	840,000	30 4	30	250	3,500	5,600	840,000	2,920	4,670	700,000	11 4	6	4 <sup>a</sup>	
4,860	7,770	1,166,000	4,000	6,400	960,000	34 8	30½	286	4,000	6,400	960,000	3,330	5,330	800,000	12 2	6	4 <sup>a</sup>	
5,470	8,750	1,313,000	4,500	7,200	1,080,000	39 1	31½	322	4,500	7,200	1,080,000	3,750	6,000	900,000	13 4	6	4 <sup>a</sup>	
6,080	9,720	1,459,000	5,000	8,000	1,200,000	43 5	31½	358	5,000	8,000	1,200,000	4,170	6,670	1,000,000	14 5	6	4 <sup>a</sup>	
7,290	11,660	1,750,000	6,000	9,600	1,440,000	52 1	32½	429	6,000	9,600	1,440,000	5,000	8,000	1,200,000	16 4	8	4 <sup>a</sup>	
8,500	13,600	2,040,000	7,000	11,200	1,680,000	60 8	34	500	7,000	11,200	1,680,000	5,830	9,330	1,400,000	18 1	8	4 <sup>a</sup>	
10,330	16,520	2,479,000	8,500	13,600	2,040,000	73 8	35½	608	8,500	13,600	2,040,000	7,080	11,330	1,700,000	20 5	8	4	
12,150	19,440	2,916,000	10,000	16,000	2,400,000	86 8	37½	715	10,000	16,000	2,400,000	8,330	13,330	2,000,000	22 5	8	4	
15,180	24,280	3,643,000	12,500	20,000	3,000,000	108 5	40½	893	12,500	20,000	3,000,000	10,420	16,700	2,500,000	25 6	8	4	
18,220	29,150	4,373,000	15,000	24,000	3,600,000	130 2	43	1,072	15,000	24,000	3,600,000	12,500	20,000	3,000,000	28 4	8	4	
21,250	34,000	5,100,000	17,500	28,000	4,200,000	151 8	46	1,250	17,500	28,000	4,200,000	14,580	23,330	3,500,000	30 9	8	4	
24,290	38,860	5,830,000	20,000	32,000	4,800,000	173 5	48½	1,429	20,000	32,000	4,800,000	16,670	26,670	4,000,000	33 2	8	4	
30,360	48,570	7,286,000	25,000	40,000	6,000,000	216 9	51½	1,786	25,000	40,000	6,000,000	20,830	33,330	5,000,000	37 4	10	6	
36,430	58,280	8,743,000	30,000	48,000	7,200,000	260 3	60½	2,143	30,000	48,000	7,200,000	25,000	40,000	6,000,000	41 2	10	6	
42,500	68,000	10,200,000	35,000	56,000	8,400,000	303 6	66	2,500	35,000	56,000	8,400,000	29,170	46,670	7,000,000	44 7	10	6	

<sup>a</sup> Oil, gas, or bituminous stoker-fired coal. Minimum furnace volumes for anthracite, stoker-fired, are not specified in this code.<sup>b</sup> Bituminous stoker-fired.<sup>c</sup> The return tapping sizes shown for boilers having 129 to 500 sq ft heating surface, inclusive, are adequate for forced hot water.



design has the lower section circular in cross section, which avoids the necessity of stays but at the expense of greater width.

### Water-leg Fire-tube Boilers

**Firebox Boilers.** This type of unit has a portion or all of the furnace volume covered by steel plate in contact with the boiler water, and consequently there is no

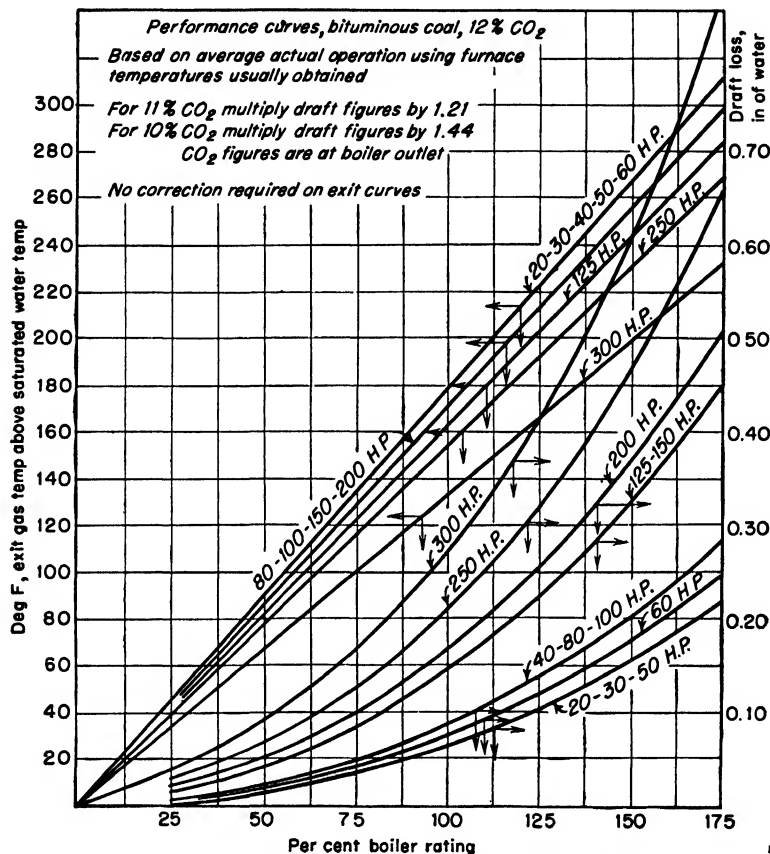


FIG. 21-8. Performance of two-pass HRT boilers—Economic.

need for refractory in the furnace. They are compact in design and can be shipped as a unit from the factory. Externally fired units are more expensive, but the firebox boiler does not require the expense of brickwork or its maintenance. Having the furnace contained in the steelwork avoids air leaks through the setting common with poorly laid or poorly maintained brickwork.

The furnace sides in firebox boilers cannot exceed about 350°F, the temperature of the water contained, and therefore do little toward promoting proper combustion in the furnace. (The cold furnace condition is alleviated in railroad locomotive boilers which are fitted with a refractory arch that heats up and raises the furnace temperature.)

**Water-leg Boilers.** In this design of firebox boilers, a vertical water leg is placed on each side of the furnace. This construction makes the unit self-contained and

eliminates the need of a setting and refractory lining. The vertical walls are subject to the boiler pressure and must be stayed. The locomotive type is of such design, the rugged construction making it suitable for portable service.

Figure 21-10 illustrates a locomotive type of boiler in two-pass design. It is equipped with a downdraft water-tube grate in the firebox. A refractory header diverts the draft down through the fuel bed so that partly consumed gases will pass

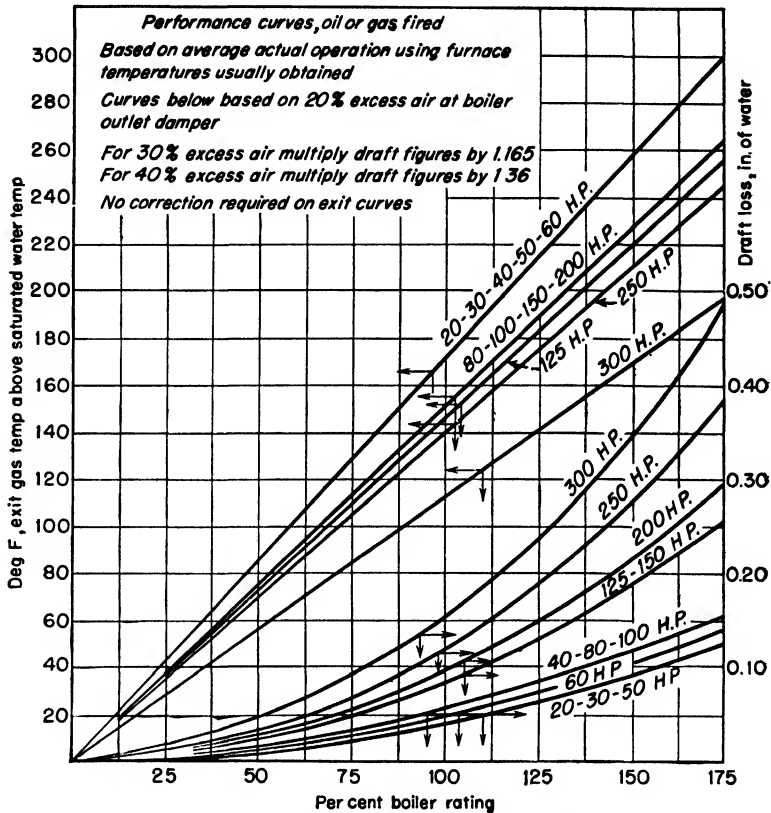


FIG. 21-9. Performance of two-pass HRT boilers—Economic.

over hot coals that have fallen through onto the lower shaking grate, to complete combustion. This type of boiler is seldom used any more.

### Heating Boilers

The Steel Boiler Institute Ratings for Commercial Steel Boilers are given in Table 21-1. Virtually all manufacturers of these types conform to this rating system. Copies of the Steel Boiler Rating Code, which also covers steel residential boilers, can be secured from the Steel Boiler Institute, Philadelphia, Pa.

**Heating Surface.** The SBI rating of a boiler, expressed in square feet of steam radiation, in which hand-fired solid fuel is burned, is equal to fourteen times the heating surface of the boiler in square feet.

The SBI rating of a boiler, expressed in square feet of steam radiation, in which

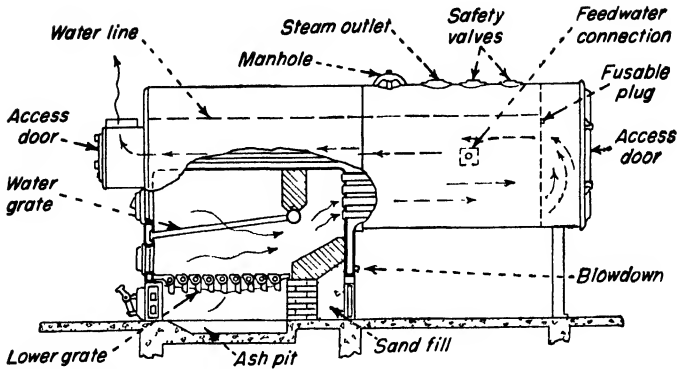


FIG. 21-10. Firebox-type boiler—two-pass locomotive type. Coal is fired on top of water-tube grate in the firebox. A refractory header diverts the gases down through the bed of burning coal, which then pass to the back of the boiler, and return to the front to the flue by means of a set of return tubes.

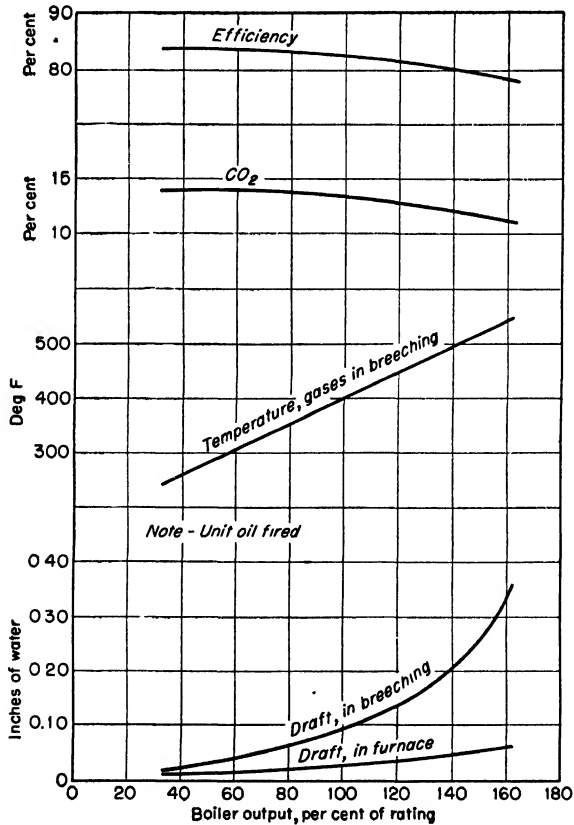


FIG. 21-11. Performance characteristics of locomotive-type boiler. Although the test was run on a Kewanee type C boiler, the results are typical of the locomotive-type boiler. (Kewanee Boiler Corp.)

solid fuel is mechanically fired, or in which oil or gas is burned, is equal to seventeen times the heating surface of the boiler in square feet.

$$1 \text{ sq ft of steam radiation} = 240 \text{ Btu/hr}$$

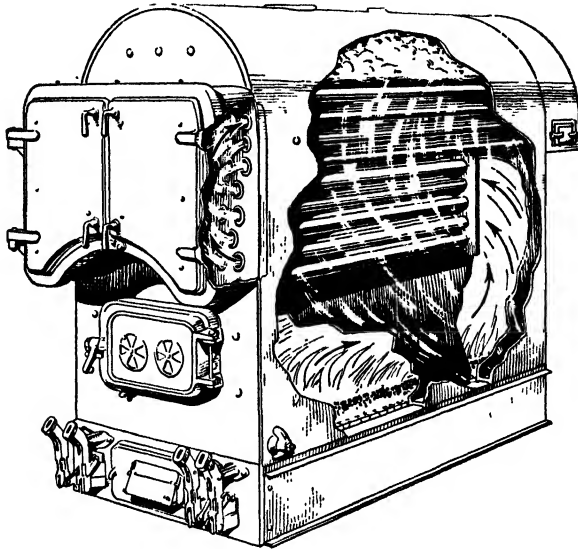


FIG. 21-12. Three-pass water-leg steel-heating boiler. (Fitzgibbons Boiler Co., type D.)

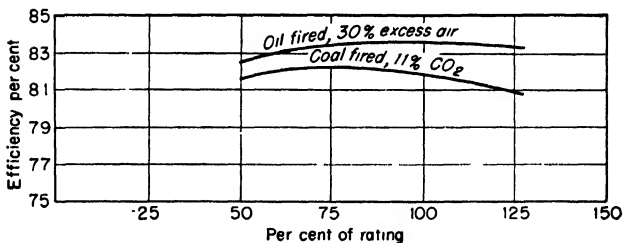


FIG. 21-13. Performance characteristics of three-pass water-leg boiler. Heating boiler of 1,250 sq ft of heating surface, 15-psi working pressure. Coal-fired curves are based upon coal having 13,900 Btu/lb as fired; oil-fired curve is based upon bunker C having 18,600 Btu/lb as fired.

**Grate Area.** The grate area shall not be less than that determined by the following formulas:

$$G = \sqrt{\frac{R - 200}{25.5}}$$

For boilers with SBI ratings of 4,000 sq ft of steam radiation and larger,

$$G = \sqrt{\frac{R - 1,500}{16.8}}$$

where  $G$  = grate area, sq ft

$R$  = SBI rating, sq ft steam radiation

**Furnace Volume.** The furnace volume for a boiler in which pulverized fuel or gas or stoker-fired bituminous coal is burned shall be not less than 1 cu ft for every 140

sq ft of steam SBI rating. No minimum furnace volume need be specified for mechanically fired boilers burning anthracite.

**Furnace Height.** Furnace height shall be the vertical distance from the bottom of the water leg to the crown sheet measured midway between the side walls and midway between the front and back (or bridge wall if used) of the furnace.

The furnace heights for bituminous coal stoker-fired boilers shall be not less than those shown in Table 21-1, column (8).

If the minimum furnace height is not contained above the bottom of the water leg of a boiler, the manufacturer shall by illustration, text, and table of dimensions in

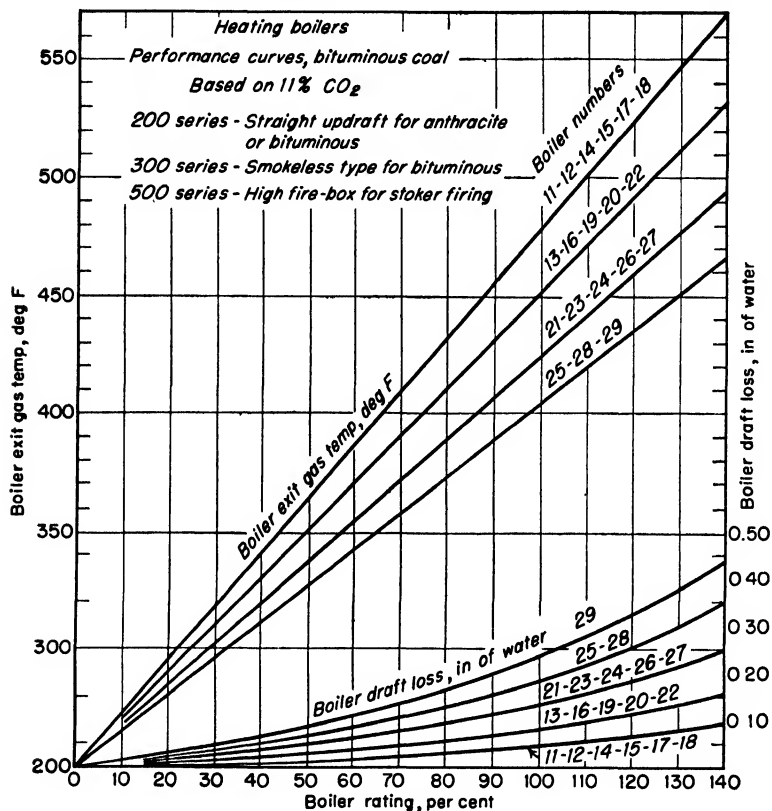


FIG. 21-14. Performance characteristics of three-pass water-leg boilers. Heating boilers, 200-300-500 series, bituminous coal, 15-psi working pressure. (Erie City Iron Works.)

his catalogue indicate clearly that the minimum furnace heights are to be obtained by setting the boiler on an extended base.

**Minimum Data to be Shown on Boiler.**

1. Manufacturer's name and address
2. Boiler number and type
3. SBI symbol
4. Heating surface in square feet

**Steel Boiler Institute Code.** The steel heating boiler has been rather highly standardized through widespread adoption of the rating and dimensional code shown as Table 21-1.

**Multipass Water-leg Boilers.** Firebox boilers of the two-pass type resemble the brick-set two-pass boiler, previously shown in Fig. 21-10. The water leg that surrounds the sides of the furnace replaces the brickwork and makes the unit self-contained. Illustrated in Fig. 21-12 is a three-pass water-leg boiler that is used for heating service and hence is designed for a maximum pressure of 15 psi. With the proper modifications, it can be used with anthracite, bituminous (hand- or stoker-fired), or gas or oil. The firebox either extends almost the full length of the boiler or may be cut off by brickwork as firing methods dictate. The gases return to the front

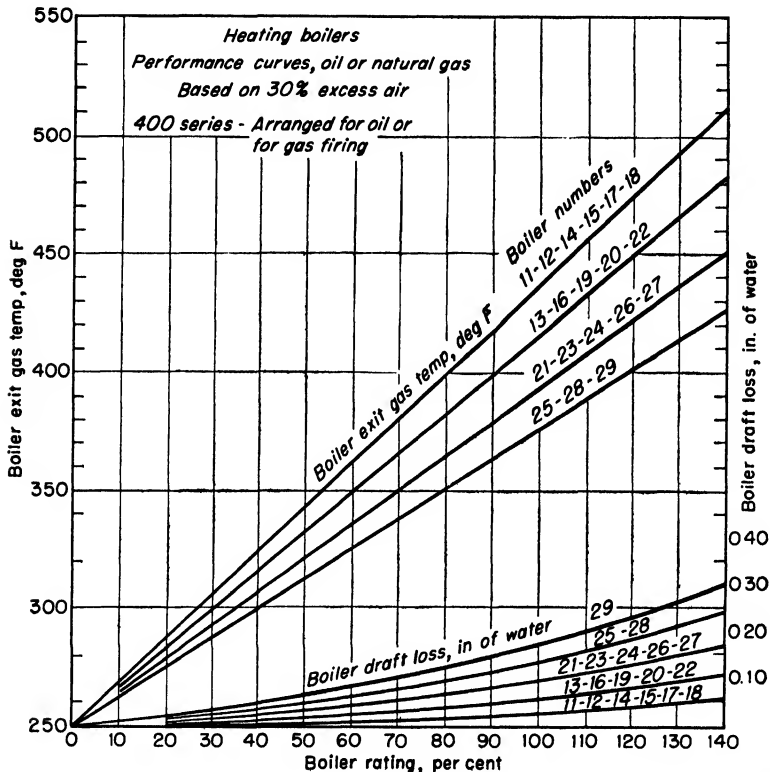


FIG. 21-15. Performance characteristics of three-pass water-leg boilers. Heating boilers, 400 series, oil or natural gas, 15-psi working pressure. (Erie City Iron Works.)

of the boiler through the lower section of tubes and then pass to the back of the boiler and to the flue through the upper section of tubes.

**Special Boilers for Close Clearances with Split Fireboxes.** A water-leg boiler of the multipass type shown as Fig. 21-16 is designed for conditions of minimum access. Hence dimensions are given as Table 21-2. This boiler is often convenient for replacements, where limitations of doorways, etc., would limit the use of other prefabricated units. The knockdown design permits the boiler to be disassembled in three or four parts: the shell (oval or round), the firebox in either one or two sections, and the base. These units, designed for heating service, have a maximum working pressure of 15 psi for steam and 30 psi for water.

**Table 21-2. Sizes and Dimensions of Pacific Split-firebox Boilers**  
(See Fig. 21-16 for key to dimensions. All dimensions in inches)

Catalogue No.	SBI rating, sq ft		A	B	C	D	E	2 × B		F	G	H	I	J	K	L
	Steam	Water						Length over-all	Width over-all							
Oval-shell Type, Low-water-line Boilers																
2982	2,680	4,280	30½	20½	42	37½	79¾	41¾	41¾	72½	59½	12	54½	39	19	9½
2983	3,160	5,050	30½	20½	42	37½	88¾	41¾	41¾	72½	59½	12	63½	39	18	9½
2984	3,650	5,840	30½	20½	42	37½	97¾	41¾	41¾	72½	59½	12	70½	39	18	9½
3381	4,250	6,800	34½	22½	46½	46½	88¾	45	45	83	68½	12	62½	43¾	20	10½
3382	4,860	7,770	34½	22½	46½	46½	97¾	45	45	83	68½	12	69½	43¾	20	10½
3383	5,470	8,750	34½	22½	46½	46½	104¾	45	45	83	68½	12	76½	43¾	20	10½
3384	6,080	9,720	34½	22½	46½	46½	112¾	45	45	83	68½	12	84½	43¾	20	10½
Oval-shell Type, High-firebox Boilers																
2992	2,680	4,280	30½	20½	49½	37½	77	41¾	41¾	82	69	14	52½	39	17	9½
2993	3,160	5,050	30½	20½	49½	37½	86	41¾	41¾	82	69	14	60½	39	18	9½
2994	3,650	5,840	30½	20½	49½	37½	95	41¾	41¾	82	69	14	69½	39	18	9½
3391	4,250	6,800	34½	22½	54½	46½	87	45	45	92½	78	14	58½	43¾	20	10½
3392	4,860	7,770	34½	22½	54½	46½	95	45	45	92½	78	14	66½	43¾	20	10½
3393	5,470	8,750	34½	22½	54½	46½	103	45	45	92½	78	14	74½	43¾	20	10½
3394	6,080	9,720	34½	22½	54½	46½	110	45	45	92½	78	14	81½	43¾	20	10½
Round-shell Type, Low-water-line Boilers																
4081	7,290	11,660	41	24½	45½	37½	121½	49	49	82½	68	12	93½	50	19½	10½
4781	8,500	13,600	48	28½	52½	37½	108½	56½	56½	94½	78	12	78½	57	19½	12½
4782	10,330	16,520	48	28½	52½	37½	123½	56½	56½	94½	78	12	93½	57	19½	12½
5281	12,150	19,440	53	30½	55½	30½	125½	61½	61½	99½	82	12	93½	62	19½	14½
5282	15,180	24,280	53	30½	55½	30½	146½	61½	61½	99½	82	12	114½	62	19½	14½
6081	18,220	29,150	61	34½	60	34½	137½	69½	69½	109	90	12	102½	69¾	22	15½
6082	21,250	34,000	61	34½	60	34½	153½	69½	69½	109	90	12	120½	69¾	22	15
6781	24,290	38,860	68½	38½	66½	38½	150½	76½	76½	121	98½	15	114½	77	22	16
6782	30,360	48,570	68½	38½	66½	38½	177	76½	76½	121	106	15	140½	77	22	16
7581	36,430	58,280	76½	42½	70½	42½	169½	85½	85½	128¾	106	15	131½	85½	22	17½
7582	42,500	68,000	76½	42½	70½	42½	190½	85½	85½	128¾	106	15	152½	85½	22	17½

Table 21-2. Sizes and Dimensions of Pacific Split-firebox Boilers. (Continued)

Catalogue No.	SBI rating, sq ft		A	B	C	D	E	2 × B	F	G	H	I	J	K	L
	Steam	Water													
Round-shell Type, High-firebox Boilers															
4091	7,290	11,660	41	24½	53¼		118¾	49	92	77½	14	90¼	50	19½	10½
4791	8,500	13,600	48	28½	55¼		106¾	56½	99¼	83	14	76¼	57	19½	12½
4792	10,330	16,520	48	28½	58¾		123¾	56½	102¾	86½	14	93¼	57	19½	12½
5291	12,150	19,440	53	30¾	61¾		122¾	62½	110¾	93½	17	90¼	62	19½	14½
5292	15,180	24,280	53	30¾	64½		143¾	62½	113½	96½	17	111¼	62	19½	14½
6091	18,220	29,150	61	34¾	70¼		137¾	70¼	124¼	105¼	17	102¼	69¾	22	15
6092	21,250	34,000	61	34¾	76		149¾	70¼	130	111	17	114¼	69¾	22	15
6791	24,280	38,860	68¼	38¼	80½		147¾	77¼	137	114½	17	111¼	77	22	16
6792	30,360	48,570	68¼	38¼	86¼		172¼	77¼	142¾	120¼	17	135¾	77	22	16
7591	36,430	58,280	76¼	42¾	102		165¼	85½	166¼	143½	21	127¼	85¼	22	17½
7592	42,500	68,000	76¼	42¾	102		184¾	85½	166¼	143½	21	146¾	85¼	22	17½



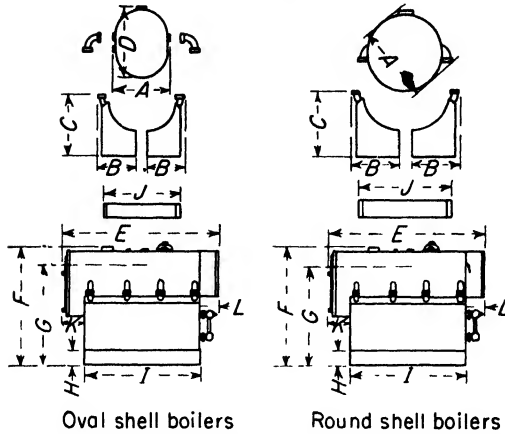


FIG. 21-16. Pacific steel boilers. Key to dimensions in Table 21-2.

**Vertical Water-leg Boilers.** Another variation of the firebox boiler is the vertical design. Although one of the oldest types, it is not used to any extent. The unit is self-contained and, because of the small floor area required, is useful mostly for restricted spaces. These boilers are relatively high, and sufficient vertical space must thus be allowed, plus additional room for the vertical removal of tubes.

Most designs are of the exposed-tube type, i.e., the water level in the boiler is below the upper tube sheet so that the tube area above the water line is cooled by steam alone, producing, in some designs, a superheated steam. There is the possibility of tube overheating with subsequent leakage at the tube sheet. In the submerged-tube design, the tube sheet is in contact with the water which avoids overheating. In the Manning design, the furnace volume and grate area are increased by using a greater diameter of shell at the furnace and narrowing the shell above the furnace.

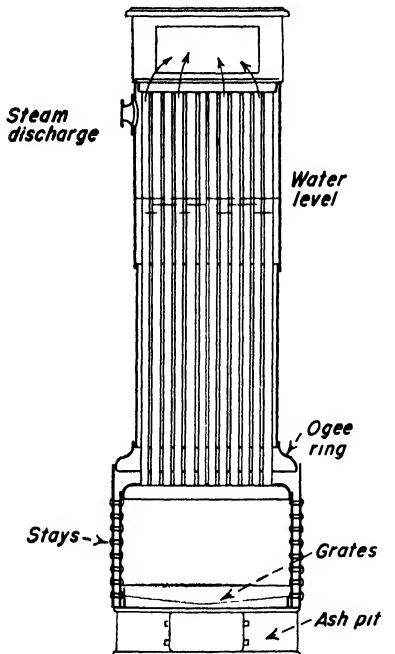


FIG. 21-17. Vertical fire-tube boiler. This Manning boiler has the enlarged lower shell for greater furnace volume and grate area. The tubes are of the exposed type, that is the water level is below the upper tube sheet. Gases pass from the furnace vertically upwards through the tubes. (*The Bigelow Company.*)

**Scotch Marine Boiler.** This type of firebox boiler can be classified as a horizontal-return tubular boiler having a cylindrical internal furnace that is completely surrounded by the boiler water. The Scotch marine boiler is of the wet-back type, i.e., the combustion chamber is also completely surrounded by the boiler water (Fig. 21-18). This construction produces a compact furnace-boiler installation, with minimum length

due to the short tubes. In order to prevent the collapse of the furnace due to the pressure surrounding it, the furnace is stiffened with corrugations. Some designs incorporate stiffening rings spaced at regular intervals, or stays to the main shell to resist these collapsing forces. The flat surfaces of the combustion chamber must be carefully stayed at the areas unsupported by the tubes, or these surfaces will bulge and rupture. These boilers have from one to four furnaces about 7 to 8 ft long and

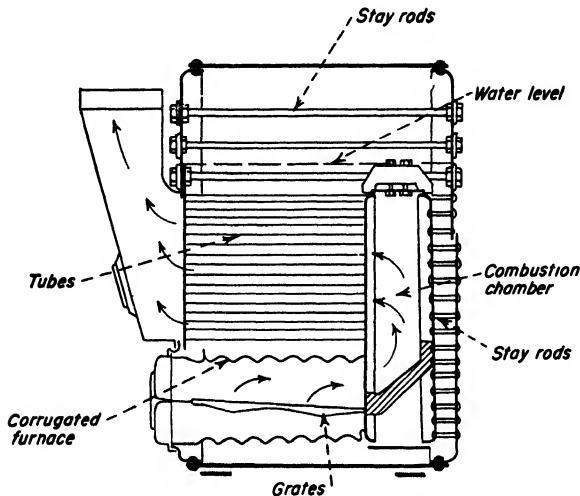


FIG. 21-18. Scotch marine or wet-back boiler. From the corrugated furnace the gases pass into the combustion chamber and then into the tubes to the front of the boiler to the flue. (Barnard, William N., Frank O. Ellenwood, Clarence F. Hirshfeld, "Elements of Heat Power Engineering," 3 ed., John Wiley & Sons, Inc., 1933, p. 678.)

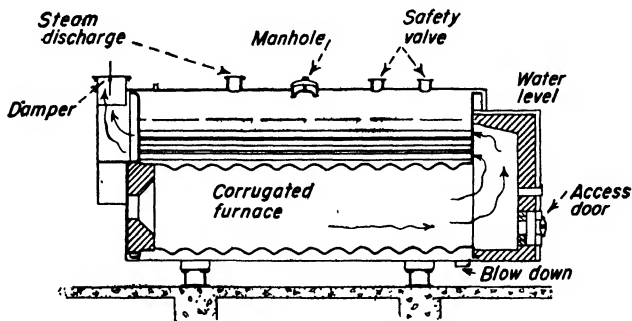


FIG. 21-19. Scotch dry-back boiler, oil-fired. Gases pass from the furnace to the back and then to the front to the flue by means of the tubes. (The Bigelow Company.)

have been built for pressures up to 300 psi. Their relatively high cost is offset by the lack of need of a setting. These types are also made double-ended; *i.e.*, the boiler is made of approximately double length and is fired from each end.

Scotch boilers have the **advantage** of being readily accessible for maintenance and repairs. Since they have generous steam-releasing surface and large steam volume they have a large steam capacity. Since their construction is simple, they require only a minimum engineering skill to operate and will produce reasonable efficiency. They are short in length and complete in themselves. They can be operated on

impure water while other types of boilers require reasonably fresh water. These

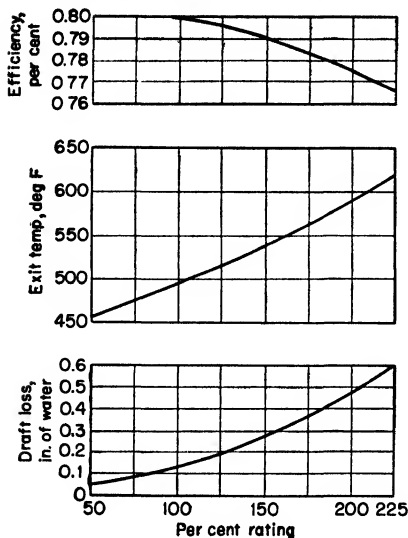


FIG. 21-20. Performance characteristics of Scotch dry-back boiler. Predicted performance for 250-hp boiler, working pressure 175 psi, 200° feed, fuel-oil bunker C—18,500 Btu/lb. (*The Bigelow Company.*)

advantages make them particularly well adapted to marine service or where space is valuable.

The Scotch boilers possess a number of **disadvantages**. In general, their large bulk of water prevents them from raising steam rapidly, they do not readily respond to rapid demands of steam loads, and the large volume of water makes them heavy and bulky. These large volumes of steam and water make them extremely hazardous in case of an explosion.

The trend toward higher performance efficiencies has resulted in the replacing of the Scotch boiler by the more modern designs of water-tube boilers.

**Dry-back Scotch boiler** is a modified Scotch marine boiler that is used for stationary service. In this design, the combustion chamber (refractory-lined) is placed outside the boiler shell and consequently is not subjected to the pressure forces present in the wet-back type (Fig. 21-19). This simplifies the construction and reduces the costs. They are particularly well adapted to conditions where the

over-all height is restricted, as in office buildings. High-volatile coals are not suitably burned in this type. The poor circulation characteristics of the lower shell cause

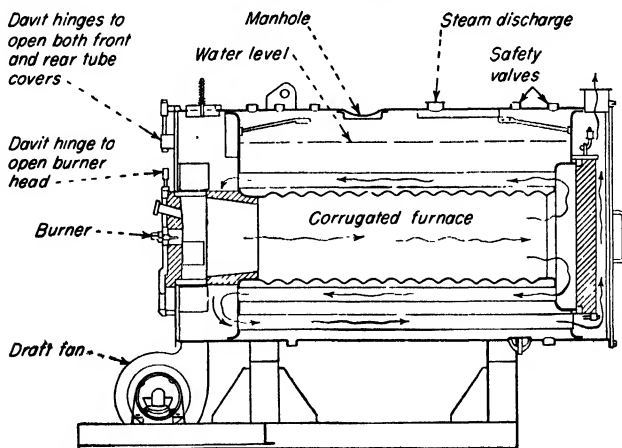


FIG. 21-21. Three-pass package unit. The gases pass through the corrugated furnace to the rear and then through tubes to the front. The last pass carries the gases to the back and to the flue. The front and rear covers swing out on the davits to give access to the tubes for cleaning. (*Ames Iron Works.*)

unequal expansions and contractions of the shell and tubes, tending to cause tube leakage.

**Fire-tube Package Units.** Both the fire-tube and the water-tube construction are used in the development of the "package" units. In these types, the boiler, feed-water pump, controls, draft fans, and firing equipment for gas or oil are all mounted on a single base. The elements are proportioned to operate effectively together so that the responsibility rests on one manufacturer. Since the unit is self-contained, it is shipped complete to the purchaser. Usually the only work to be done to place

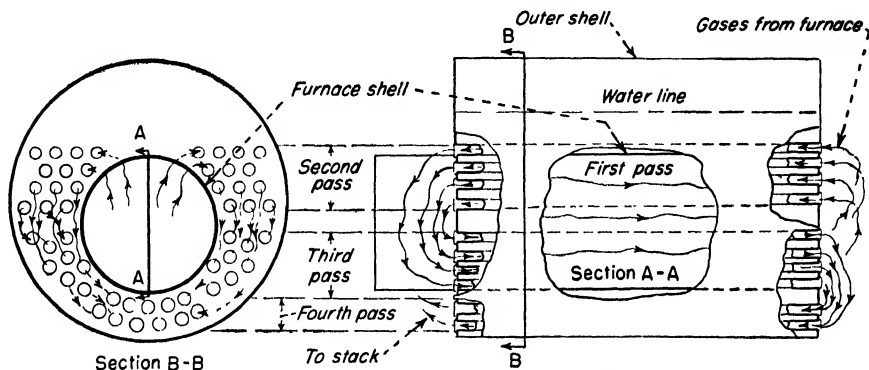


FIG. 21-22. Four-pass package unit. Illustrated is the diagrammatic sketch of a four-pass firebox package unit. Combustion occurs in the furnace shell and pass to the rear forming the first pass. The second pass occurs when the gases move from the furnace shell to the front of the unit by means of the upper bank of tubes. The third pass is to the rear through the middle banks of tubes, and the fourth pass is to the front by means of the lowest bank of tubes. The gases then go to the stack. In this drawing the baffles have been omitted for the sake of clarity.

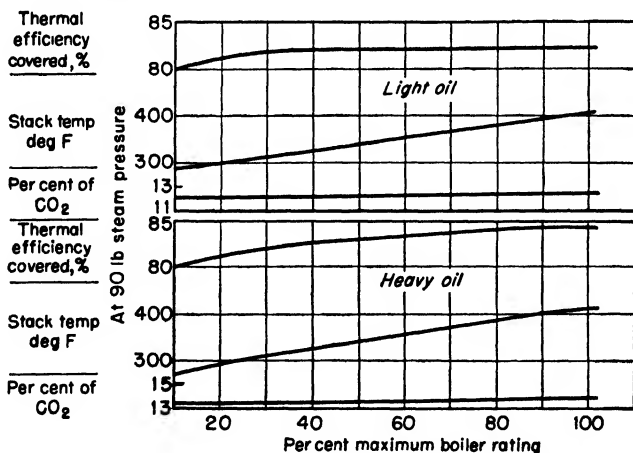


FIG. 21-23. Performance of four-pass package unit. (Preferred Utilities Mfg. Corp.)

the unit in service after mounting is the connecting of electricity, steam, water, fuel, and flue. The construction resembles the Scotch dry-back, having a central cylindrical furnace into which the flame is directed. In order to secure high heat absorption with long runs, the gases flow through either three or four passes, depending on the design. In order to take care of the higher draft loss of the multipass design, mechanical draft is installed which eliminates the necessity for stack draft, and only a flue need be installed.

**Table 21-3. Sizes and Capacities of Typical Horizontal-return Tubular Boilers<sup>1</sup>**

Rated hp.....	45	50	60	80	100	125	150	180	200	225	250	300
Diam, in . . . . .	48	48	54	60	66	72	72	78 <sup>a</sup>	78 <sup>a</sup>	84 <sup>a</sup>	84 <sup>a</sup>	90 <sup>a</sup>
Length, ft . . . . .	14	16	14	16	16	16	18	18	20	18	20	20
No. of 4-in. tubes . . . . .	28	28	36	44	54	70	70	88	88	108	108	140
Length of grate, in . . . . .	54	54	54	54	54	54	60	72	78	78	84	90

<sup>1</sup> Erie City Iron Works.<sup>a</sup> Boilers over 72 in. in diameter required by code to have overhead suspension.**Table 21-4. Sizes and Capacities of Two-pass HRT Boilers, Economic Type<sup>1</sup>**

Rated hp . . . . .	20	30	40	50	60	80	100	125	150	200	250	300
Diam, in . . . . .	30½	36	40	40½	44½	54	54	60	60	66	72	78
Heating surface, sq ft . . . . .	203	300	400	504	608	813	1,000	1,263	1,500	2,002	2,514	3,000
Grate length, in . . . . .	42	48	54	54	60	60	72	72	78	90	96	108
Grate width, in . . . . .	30½	36	40	44½	44½	54	54	60	60	66	72	78
Grate area, sq ft . . . . .	8 9	12	15	16 7	18 5	22.5	27	30	32.5	41 2	48	59.5

<sup>1</sup> Erie City Iron Works.**Table 21-5. Sizes and Capacities of Scotch Dry-back Boilers<sup>1</sup>**

Specifications for Oil-fired Boilers													
Boiler hp	25	30	40	50	60	75	100	125	150	175	200	250	300
Heating surface, sq ft	221	279	376	450	576	736	1,014	1,246	1,504	1,769	2,015	2,523	3,024
Space required for tube removal . . . . .	6'5"	6'5"	7'3"	8'9"	8'9"	9'7"	11'4"	12'2"	12'8"	12'6"	12'10"	13'8"	14'8"
Specifications for Coal-fired Boilers													
Heating surface, sq ft. . . . .	209	265	362	431	553	710	981	1,208	1,457	1,719	1,960		
Grate length . . . . .	4'0"	4'0"	5'0"	5'0"	5'6"	6'0"	6'6"	7'0"	8'0"	8'0"	8'6"		
Grate area, sq ft . . . . .	8	9	12 5	12.5	15 1	18 0	21.1	24.5	30 0	32 0	36 3		

NOTE: Standard pressures are 100, 125, 150, and 200 psi. When required, unit may be designed for higher pressures.

<sup>1</sup> The Bigelow Co.**Table 21-6. Sizes and Capacities of Vertical-firebox Boilers<sup>1</sup>**

Boiler No . . . . .	5	6	7	8	9	10	11	12
Hp based on 10 sq ft of water-heating surface	108	134	165	200	255	298	345	378
Total heating surface, sq ft	1,446	1,794	2,202	2,681	3,345	3,914	4,548	4,971
Water-heating surface, sq ft	1,082	1,344	1,647	2,001	2,548	2,975	3,457	3,776
Superheating surface, sq ft	364	450	555	680	797	939	1,091	1,195
Additional heating surface for each foot of tubes, sq ft. . . . .	91	113	139	170	199	235	273	299

<sup>1</sup> The Bigelow Co.

**Table 21-7. Sizes and Capacities of Locomotive-type Boilers<sup>1</sup>**  
(For steam pressures of 100, 125, and 150 psi)

Boiler No.....	376	377	378	379	380	381	382	383
Rating								
Steam radiation, sq ft ..	3,500	4,000	4,500	5,000	6,000	7,000	8,500	10,000
Hp ..	25	29	32	36	43	50	61	72
1,000 Btu/hr ..	840	960	1,080	1,200	1,440	1,680	2,040	2,400
Heating surface (SBI code min), sq ft ..	250	286	322	358	429	500	608	715
Grate area (SBI code min), sq ft ..	11 4	12 2	13 4	14 5	16 4	18 1	20 5	22 5
Boiler diam, in... ..	42	42	48	48	54	54	60	60
Boiler length .....	8'3"	9'3"	8'9"	9'6½"	9'4"	12'11"	12'8¼"	14'9"
Boiler No .....	384	385	386	387	388	389	390	
Rating:								
Steam radiation, sq ft.....	12,500	15,000	17,500	20,000	25,000	30,000	35,000	
Hp .....	89	107	125	143	179	214	250	
1,000 Btu/hr.....	3,000	3,600	4,200	4,800	6,000	7,200	8,400	
Heating surface (SBI code min), sq ft ..	893	1,072	1,250	1,429	1,786	2,143	2,500	
Grate area (SBI code min), sq ft ..	25 6	28 4	30 9	33 2	37 4	41 2	44 7	
Boiler diam, in... ..	66	66	72	78	78	84	84	
Boiler length .....	14'11"	17'4"	16'5"	20'7½"	20'7½"	19'11"	22'8"	

<sup>1</sup> Kewanee Boiler Corp.

**Table 21-8. Capacities and Performance of Some Three-pass Package Units<sup>1</sup>**

Size No . . . . .	A-150	A-200	A-250	A-300
Rated hp .....	150	200	250	300
Lb steam/hr .....	5,180	6,900	8,630	10,350
Btu/hr .....	5,025,000	6,700,000	8,375,000	10,050,000
Equivalent direct cast-iron radiation, steam/sq ft ..	20,938	27,917	34,896	41,875
Equivalent direct cast-iron radiation, water/sq ft ..	33,500	44,667	55,834	67,000
Full-load firing rate, No. 5 oil/gal/hr .....	42.5	56 5	70 5	84 5
Full-load firing rate, No. 6 or bunker C oil/gal/hr ..	41 5	55 0	69 0	82 5
Min diam gas vent required, in .....	18	20	20	22

NOTE: All figures given for boiler output are at the boiler outlet and are from and at 212°F. The full-load firing rates are based on average Btu contents of fuel as follows:

No. 5 oil .....

No. 6 or bunker C oil... ..

<sup>1</sup> Ames Iron Works.

**Table 21-9. Sizes of Four-pass Package Units<sup>1</sup>**

(Steam pressures 100 to 200 psi)

Hp ....	20	30	40	50	60	70	80	100	125
Approx rated capacity, lb steam/hr, 212°F .....	700	1,050	1,380	1,725	2,070	2,420	2,760	3,450	4,300
E.D.R. steam <sup>a</sup> .....	2,780	4,170	5,560	6,950	8,340	9,730	11,120	13,900	17,375
E.D.R. hot water <sup>a</sup> .....	4,460	6,690	8,920	11,150	13,380	15,610	17,840	22,300	27,875
Size of vent pipe, in . . . . .	8	10	10	12	12	12	15	15	16
Hp .....	150	200	250	300	350	400	450	500	
Approx rated capacity, lb steam/hr, 212°F .....	5,200	6,900	8,600	10,500	12,000	13,800	15,500	17,000	
E.D.R. steam <sup>a</sup> .....	20,850	27,800	34,750	41,700	48,650	55,600	62,500	69,500	
E.D.R. hot water <sup>a</sup> .....	33,450	44,600	55,750	66,900	78,050	89,200	100,300	111,500	
Size of vent pipe, in .....	18	20	22	24	26	28	30	30	

<sup>1</sup> Preferred Utilities Mfg. Corp.

<sup>a</sup> E.D.R. = equivalent direct radiation.

An example of the **three-pass type** is shown in Fig. 21-21. The first pass is through the tubes around the furnace to the front, and the third pass is to the rear of the furnace.

These units, as manufactured by the Ames Iron Works, Oswego, N.Y., are available in sizes from 10 to 300 hp in pressure from 15 to 200 psi with an 80 per cent guaranteed efficiency.

An example of the **four-pass type** is shown in Fig. 21-22. The gases pass to the rear of the unit through the central furnace, are brought to the front by means of the upper bank of tubes, pass to the rear by means of a middle bank of tubes, and return to the front by means of the lowest bank of tubes, and from there pass through the induced-draft fan to the vent pipe. This unit *a*, manufactured by the Preferred Utilities Corp., New York, is available in many sizes from 20 to 500 hp and for pressures up to 250 psi fired with heavy oil. For light-oil firing the four-pass unit is available in sizes from 20 up to and including 80 hp and pressures up to 250 psi. This company also has available a two-pass unit that is designed to operate fully automatically with a commercial grade of No. 2 or lighter grade of fuel oil and with a guaranteed thermal efficiency of 75 per cent, and uses the induced draft of the four-pass units. It is available in either 20- or 30-hp sizes for 15 psi design pressure.

#### Sizes and Capacities of Fire-tube Boilers

In Tables 21-3 to 21-9 are given some typical sizes and capacities available of the various fire-tube types already illustrated. It must be emphasized that, even though a manufacturer's name appears over a table, it does not mean that this is the only fabricator of this type or that these are the only sizes made. There are so many manufacturers that no attempt is made to list them. For such a tabulation refer to the "Mechanical Catalogue and Directory," published by the ASME.

### WATER-TUBE STEAM GENERATORS

**Comparison with Fire-tube Type.** The water-tube steam generator came into use long after the successful application of the fire-tube types. Small-diameter tubes and relatively small diameter drums made it possible to achieve present-day high temperatures and pressures. In order to secure high capacity in a fire-tube unit, drums of large diameter must be used to contain the large amount of tubes. In the design of thin-walled cylinders, doubling the drum or cylinder size doubles the thickness. Also, if the pressure is doubled, the thickness must also be doubled. If both the shell diameter and pressure are doubled, the thickness of the plate must be quadrupled. Consequently, the fire-tube type quickly reaches limits of size and pressure, since the shell thickness required becomes excessively thick, leading to difficulties of fabrication and of overheating and burning of the plate because of unequal distribution of temperatures. Water-tube types are not affected by these difficulties, since their elements are of small-diameter tubes, not usually over 4 in. in diameter, and the drums not usually over 66 in. in diameter. Also, the drums can be placed where they are not subjected to high temperatures. The tubes, which are not excessively thick even at high pressures, are subjected to high temperatures but can be kept from overheating by proper circulation design and use of suitable feed- and boiler-water treatment. Tubes may be added or lengthened to secure higher capacities. Because the only pressure parts which are normally exposed to the high temperatures are the tubes, which individually contain only relatively small amounts of water and steam, failure of pressure parts is confined to a localized area with a resultant increase in safety of operation.

The **water-tube steam-generator classification** is a broad grouping to cover those units which have water or steam or both circulating in tubes that are swept on the

outside by the gases passing from the furnace to the flue. Because of flexibility of arrangement possible with arrangements of drums and tubes, there are a great number of designs of steam generators available. There is very little standardization of complete units, most applications being "tailor-made" to fit the customer's requirements. In order to benefit from the economy of repetitive production, many of the elements of a number of types are standardized. This produces sufficient elasticity of design that the manufacturer may readily design and produce a wide variety of sizes and capacities of steam generators. This system is common in the low-pressure, small- and medium-capacity types, but the users of high-pressure and high-capacity units, such as central stations, discourage this practice, contending that it tends to retard progress and improvement; hence these units are completely "custom-built." There have been frequent cases, of late, within specific systems, where satisfactory existing units have been duplicated to advantage.

### Straight-tube Types

Water-tube generators may be classified according to types of tubes (straight, bent, and coil); according to the number of drums (one, two, three, four, and five drums

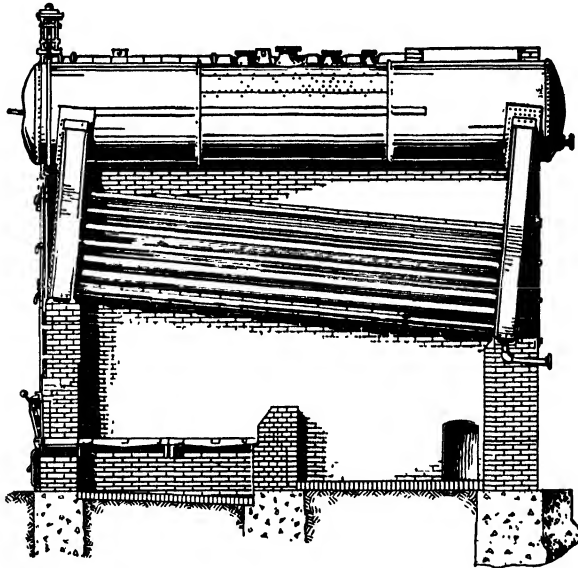


FIG. 21-24. Longitudinal-drum straight-tube boiler. This unit is equipped with box headers. The baffling directs the gases to the rear, then along the tubes to the front, and then along the bottom of the drum to the rear. (*Erie City Iron Works.*)

being the most commonly used); and according to the arrangement of the drums or headers (cross drum or longitudinal drum).

The straight-tube type has the following **advantages**:

1. Ease of fabrication of tubes. However, box and sectional headers are not always easy to fabricate.
2. For replacement only a few tubes need be kept in stock since they are identical.
3. A tube can be readily replaced without disturbing any of the others.
4. Scale can easily be removed from the inside of the tubes, by simple mechanical methods.
5. Under certain conditions, there is lower headroom.



The disadvantages are:

1. Large number of handholes giving access to the tube ends are expensive to produce. To clean all tubes, a large number of handhole covers must be removed.
2. Straight-line expansion of the tubes can set up high stresses with improper design.
3. Generally slightly higher in price than equivalent three-drum units. Generally slightly higher exit-gas temperature, because of tube-and-baffle arrangement.
4. More drum surface exposed to hot gases on longitudinal-drum type.

**Longitudinal-drum Straight-tube Type.** This design is one of the oldest of the water-tube boilers. Changes in manufacture have improved the boiler structurally,

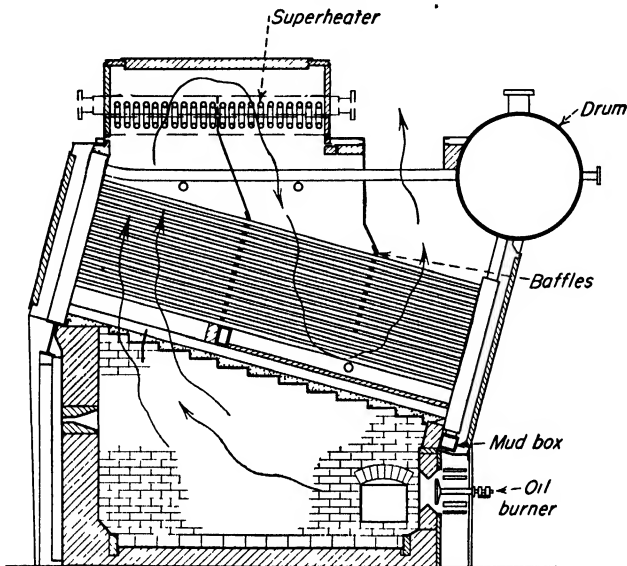


FIG. 21-25. Marine cross-drum steam generator. Cross drum, straight tube, forged steel, sectional header marine steam generator, arranged for oil firing and three flows of gases across the heating tubes. A convection superheater is placed at the top of the first and second gas passes. Units of this type were used on the Liberty ships of the U.S. Maritime Commission. Capacity 24,000 lb of steam per hour, at 220 psi, and 450°F. (Foster Wheeler.)

but the design is still fundamentally simple. They have a disadvantage, in that in order to increase the furnace width and the capacity more expensive drums must be added. This type is still used in industrial plants but is now virtually obsolete.

The longitudinal-drum type is made with the drum horizontal or with the drum sloped as conditions dictate. Headers drop from the front and the back of the drums; these headers are connected by the straight tubes. The headers are of either the box type or the sectional header. The box header is of rectangular cross section (Fig. 21-24). In order to resist internal pressure, stay bolts must be used to prevent the plates from bulging. This stay-bolt construction usually limits the maximum pressure to 300 psi. In the horizontal-baffle type, the stay bolts are hollow to permit the insertion of soot-blowing nozzles, and in the cross-baffle type they are solid except at the end where they are drilled for riveting and inspection. A handhole is located opposite each tube end. Firing is usually at the high end of the tube slope. The

header at the low end of the slope acts as the downcomer.<sup>1</sup> The blowdown pipe is located at the bottom of this header where the mud can be expected to collect, carried there by the circulation.

In the straight-tube type of boiler, the cross drum has largely superseded the longitudinal-drum boiler, particularly in the higher capacity units, because of the elasticity of design. Because of the arrangement of the longitudinal drum and the tubes, there is a very definite limit to the number of tubes and hence the amount of heating surface and capacity per drum. Also, the cross drum is a better design in that sectional headers instead of box headers can be used, thereby permitting higher pressures, and the cross-drum design places most of the drum out of contact with the hot gases. Higher capacity in the cross drum design can be secured simply by the lengthening of the drum and the tubes, which is far more economical construction for the higher capacities.

The cross-drum boiler can be equipped with a box header but is usually equipped with the **sectional header**, which, as its name implies, is a vertical header having only one or two tubes in width horizontally, usually staggered (Fig. 21-25). Enough of these sections are fastened together to secure the number of tubes required. Usually the headers are vertical with the tubes entering at an angle; but in most marine practice the header is inclined, the tube entering at right angles to the header. Since the individual header section is separate from the adjoining sections, the circulation through the header follows as many paths as there are sections. Short tubes connect the header to the drum immediately above, while horizontal circulator tubes connect the other header to the drum and complete the water circuit. The lower header is connected by a cross box which acts as a mud drum, to which are connected suitable blowdown pipes. Using the sturdy construction of the sectional header, these units are built for pressures ranging from 160 to 2,000 psi. The foregoing upper limits are based on units that have been built, but they do not necessarily represent the limits for which these designs are now recommended.

**High-capacity Sectional-header Type.** When pulverized coal came into successful use, high-capacity high-pressure straight-tube units were designed for this application. Many of the high-pressure sectional-header units were operated at evaporative rates that exceeded the previously established safe values. Some of these units experienced difficulties with water circulation. Also, with poor grades of coal, slag was deposited on the tubes at the entrance to the tube banks. This difficulty was partly solved by the **slag screen**, which consisted of the rearrangement of the lower rows of tubes in both the horizontal and the vertical direction. The spacing in both directions was increased, which gave lower gas velocities, and slag bridging between the tubes was retarded. The foregoing difficulties, together with the development of welding

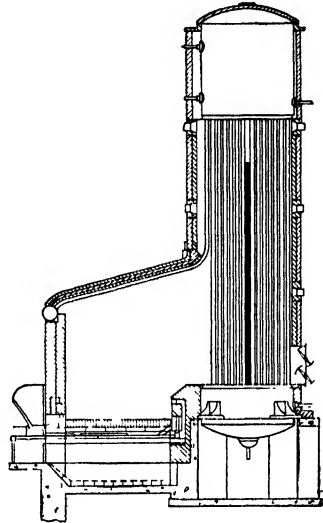


FIG. 21-26. Vertical straight water-tube boiler. Vertical water-tube unit employs upper drum for the release of steam; the lower one for mud drum. Dutch-oven furnace has water-cooled arch tied into the circulating system. Baffling is vertical. (*Power*, December, 1946.)

<sup>1</sup> Downcomer is any passage that carries cooler water from the upper level (or drum) of a steam-generating unit to the lower level (or drum).

technique, which made rapid fabrication of drums practical and economical, served to accelerate the use of bent-tube designs.

The vertical straight water-tube design utilizes the lower drum as a mud collector and the upper one for steam release. Vertical baffling directs the passage of the gases. This type is virtually obsolete (see Fig. 21-26).

### Bent-tube Types

The bent-tube types have the following advantages:

1. Elasticity of design. A large number of designs of various combinations of drums and tube arrangements is available.
2. The large number of handholes necessary with the straight-tube types is eliminated.
3. The curved tubes bow on heating if the ends are restricted, which helps to eliminate high stresses which are a characteristic of the straight tubes under similar circumstances.
4. Heat transfer is generally better because of smaller tubes and more effective baffling.
5. Higher ratings are usually feasible because of better circulation.
6. Generally they are less expensive for comparable size.
7. The three-drum type usually requires less headroom.

The disadvantages are:

1. Because of the wide variety of shapes of the tubes in a single steam generator, large numbers of tubes must be kept in stock for immediate replacement.
2. Tube cleaning is more difficult in the bent type; operations must be conducted from the inside of the drum.
3. Tube replacement is more complicated; in some designs other tubes must be removed to get at the injured tube.

**Arrangement.** The bent-tube types are characterized by the wide variety of arrangement of drums and heating surface, which gives great flexibility of design. The number of drums varies from two to five or more, the common arrangement being two and three or four. In general, the upper drum serves to release the steam, while the lower drum serves as the mud drum and has the blowdown piping connected to it. With the multidrum construction, there are several upper drums, all of which are almost totally submerged except one which serves to release the steam. In some designs, one of the drums is totally dry, into which the steam from the release drum discharges.

Tubes are 3 or  $3\frac{1}{4}$  in. in diameter, and some designs feature smaller tubes (2 or  $2\frac{1}{2}$  in.) in the rear passes. Use of the smaller tubes in rear passes, where heat transfer is almost wholly by convection, gives greater heat-absorbing area. Employing baffles to give cross travel at the rear increases heat absorption at the cost of somewhat greater draft loss. Bent-tube boilers are designed for parallel gas flow as well as cross flow, depending on proportions and allowable draft loss.

General practice for bent-tube boilers involves introducing feed water into an upper drum, usually the steam-release drum, and distributing it across the drum length. This aims at preventing a concentrated rush of comparatively cold water against drum areas, tube ends, or nozzles, resulting in differential-expansion stresses. Also, this gives better mixing of feed and boiler water. In some cases feed water enters the mud drum and is directed from there through tubes in convection passes to an upper drum. This feed-water travel through convection heating areas is akin to economizer action. As in straight-tube boilers, drums are often provided with arrangements for washing and scrubbing outgoing steam with incoming feed water.

Although bent-tube boilers display a wide variety of drum-and-tube arrangements,

there has been and is a definite trend to development of standardized designs. As might be expected, this trend is most noticeable in the smaller units, but essentially standardized designs have been developed for outputs up to and beyond 300,000 lb per hr. In the smallest size units, standardized steam generators may be factory-assembled and delivered to the site as a complete unit. Where dimensions make this impractical, subassemblies are put together at the factory, and the only site erection required is the combining of the subassemblies. In the upper size range, the amount of factory assembly is usually small, but standardization effects substantial savings in engineering and fabrication.

**Two-drum Type.** *Drum Axis Parallel to Longitudinal Axis of Furnace.* The two-drum unit, illustrated in Fig. 21-27, is a standardized steel-cased design. In sizes up to about 250 hp they may be shipped complete as a boiler-furnace unit. Larger sizes are available, adaptable to all methods of firing. In order to secure more furnace volume, all that is necessary is to lengthen the water-wall tubes. This may necessitate erection in the field, or the unit may have to be mounted on brick foundations.

The upper water and steam drum extends the whole length of the steel-insulated casing, while the lower drum is only about half the length of the upper. Bent tubes connect the upper and lower drum. A header on each side of the furnace is connected to the upper drum by the water-wall tubes.

The baffles in the main bank of tubes are vertical and are arranged to give several passes to the gases before they pass out through the unit at the top.

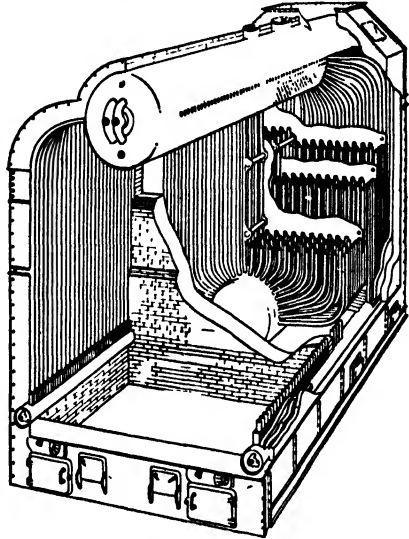


FIG. 21-27. Steel-cased two-drum unit. Gases from the furnace go through the vertically baffled passes at the rear of the unit and then pass out through the opening at the top. (Rowley, I. N., B. G. A. Skrotzki, J. L. King, J. C. McCabe, *Steam Generation, Power*, December, 1946.)

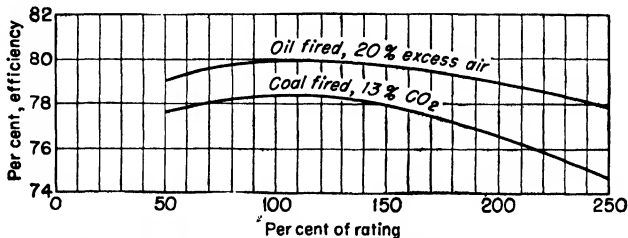
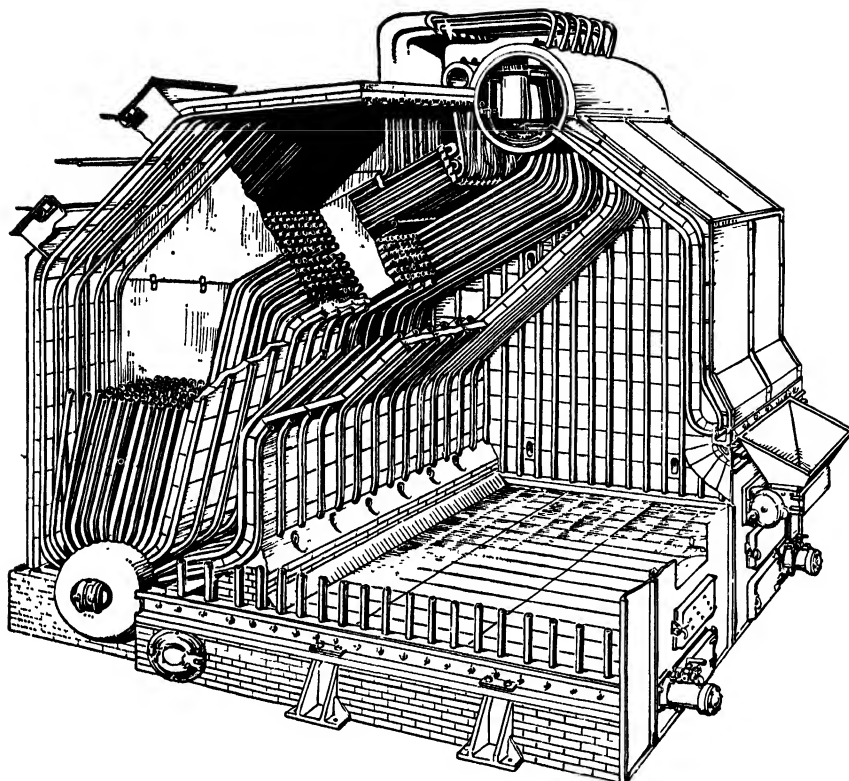


FIG. 21-28. Performance of two-drum unit, 150 hp, 150 psi. Erie City type VL boiler. Coal-fired curves are based on coal having 13,900 Btu/lb as fired. Oil-fired curves are based upon bunker C oil having 18,600 Btu/lb. (Erie City Iron Works.)

**Two-drum Integral-furnace Cross Drum, Small Capacity.** The steam generator shown in Fig. 21-29 is an application of the two-drum integral furnace to installations of lower capacity fired by stokers or oil burners. The furnace is water-cooled; the front wall, as well as the rear or bridge wall, side walls, and roof of this furnace are

FIG. 21-29. Two-drum integral furnace. (*The Babcock & Wilcox Co.*)**Table 21-10. Sizes of Two-drum Integral-furnace Boilers<sup>1</sup>**

(Capacity range: 5,000 to 50,000 lb steam/hr. Nominal rating: 200 per cent for spreader stoker, 175 per cent for underfeed stoker for coal of ash-fusion temp greater than 2200°F, and 250 per cent for oil)

Size of boiler	No. of tubes wide							
	16	20	24	28	32	36	40	44
<b>F-9:</b>								
Heating surface, sq ft	1,353	1,654	1,956	2,258	2,560	2,863	3,164	
Steam-outlet size, in	4	4	4	4	4	4	5	
Feed size, in.....	1½	1½	1½	1½	1½	2	2	
<b>F-12:</b>								
Heating surface, sq ft	1,984	2,414	2,843	3,273	3,703	4,134	4,563	
Steam-outlet size, in...	4	4	4	5	5	5	5	
Feed size, in.....	1½	1½	2	2	2	2	2	
<b>F-15:</b>								
Heating surface, sq ft		3,160	3,717	4,274	4,832	5,392	5,949	6,506
Steam-outlet size, in . .		5	5	5	6	6	6	6
Feed size, in.....		2	2	2	2½	2½	2½	2½

<sup>1</sup> Babcock & Wilcox Co.

all water-cooled. The furnace is arranged so that there is a primary combustion zone followed by an open pass. With this design the gases are thoroughly mixed while at high temperatures, thereby aiding in efficient and smokeless combustion. All baffles are vertical, thereby shedding fly ash and permitting easy tube removal. Gas flow in boiler bank is cross flow, giving maximum heat-transfer rate.

*Two-drum Medium Capacity.* One design, type VU, as shown in Fig. 21-30, is a complete steam-generating unit applicable to a wide range of load and fuel requirements. It is built to **standardized specification** and is characterized by an integrated

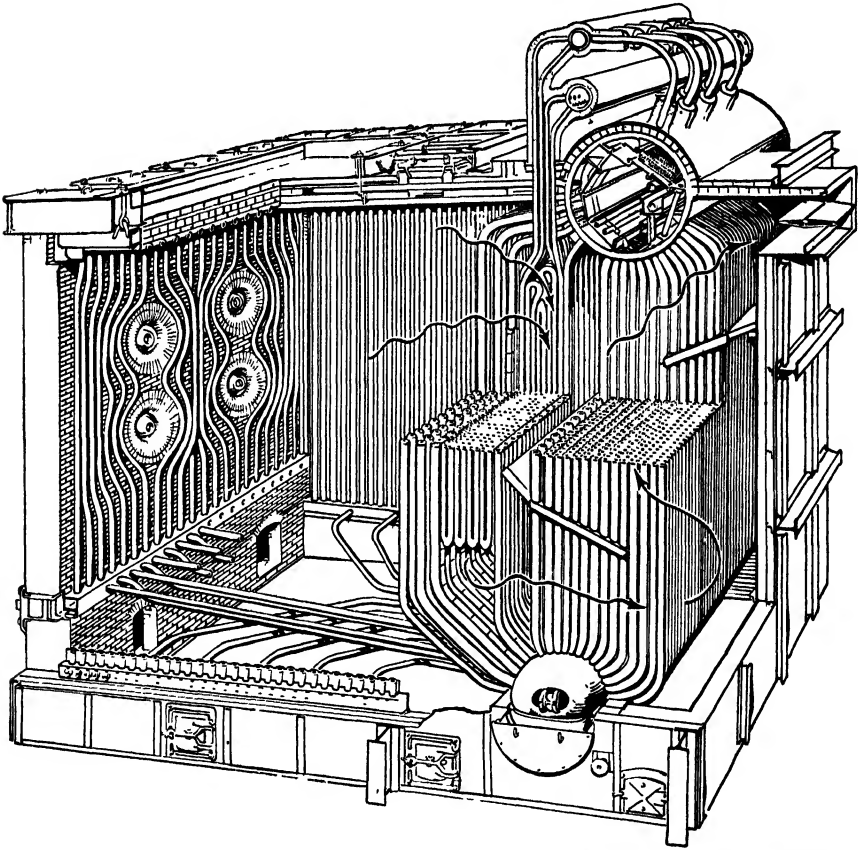


FIG. 21-30. Two drum medium-capacity unit. (*Combustion Engineering-Superheater, Inc.*)

design in which the furnace is located in front of the convection surface, rather than below it. It is a compact symmetrical assembly of furnace, boiler, and superheater surfaces. Any longitudinal section taken through the furnace from front to rear of the unit is similar to any other section taken likewise and has its own complement of furnace, water-heating surface, and superheater surface. Consequently, the gases enter the tube bank at virtually constant temperature across the entire width of the unit. This important characteristic is maintained throughout the remaining heating surfaces. The unit is usually enclosed in a welded-steel casing, although a brick

setting may be used if desired. With the airtight steel construction, all circulatory tubes or headers are located entirely within the casing, where they serve as effective heat-absorbing surfaces.

A considerable amount of latitude in application is provided by varying the dimensions of the unit in standardized increments; all the details are standardized. Installations include capacities from 15,000 to 300,000 lb steam per hr; working pressures up to 1,000 psi and total temperatures to 910°F. The unit may be supplied with or without external economizer, or with both. The air heater may be of plate, tubular, or regenerative type. This steam generator may be fired by pulverized coal, oil, gas, or mechanical stokers of the spreader, underfeed, or traveling-grate type. The furnace design may be modified to burn waste fuels such as bagasse and wood.

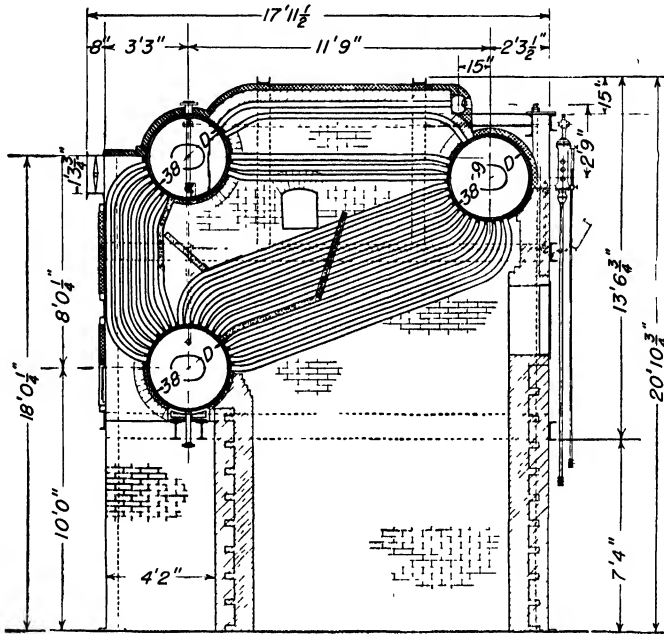


FIG. 21-31. Three-drum boiler, type 3-C. (Erie City Iron Works.)

In the boiler section, the tubes in the front bank are subject to high rates of heat absorption and are 3 in. in diameter to provide for adequate circulation. The number of rows in this bank may be varied to satisfy superheater requirements. The first row of tubes in the second bank is used as a baffle support, and the tubes are 3 in. in diameter to provide strength. The remaining tubes of the second bank, being subject to relatively lower temperatures, are 2 in. in diameter to provide additional heating surface in this space. The upper drum may vary in diameter from 48 to 66 in. The steam generated in the furnace and boiler tubes is discharged into the upper drum where the entrained water is removed by baffles and screens.

All furnace tubes are 3 in. in diameter and are connected to the boiler drums through headers and circulators. The amount of water-cooled surface depends on the method of firing and the probable furnace conditions. For pulverized-coal firing, the tubes are spaced at adequate distance to prevent slag bridging.

**Three-drum Type.** The boiler shown in Fig. 21-31 is of the three-drum type. The upper two drums serve as both steam and water drums. The steam leaves the rear drum directly through a nozzle or through a bank of tubes which extend the entire width of the boiler, the tubes connecting into a discharge header. These tubes

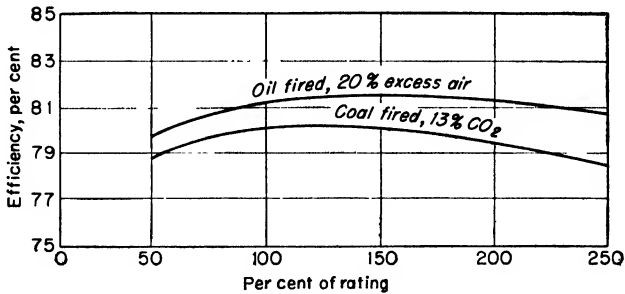


FIG. 21-32. Performance curves of three-drum boiler. Boiler as tested—150 hp, 150-psi working pressure, four water walls. Coal-fired curve is based upon coal having 13,900 Btu/lb as fired. Oil-fired curve is based upon bunker C having 18,600 Btu/lb.

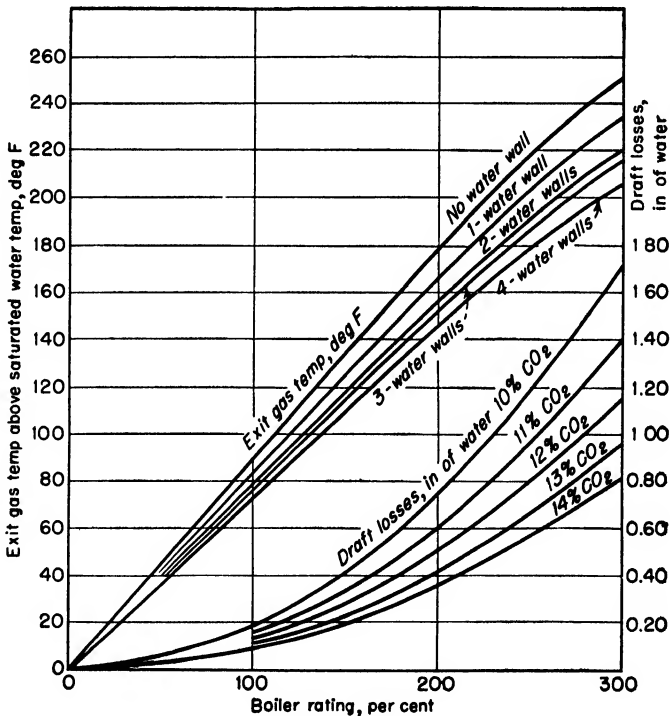


FIG. 21-33. Performance curves of three-drum boiler, bituminous-coal fired. Set 12 ft, regular baffles.

are inside the setting in the path of the gases in the second pass of the boiler and serve to dry and superheat the steam as it passes from the rear drum through the tubes to the header situated above the front drum. Steam delivery with 8 to 10°F of superheat is not uncommon. Space is provided for the installation of any standard type



of superheater without interfering with the accessibility of the boiler. The smaller type units can be shipped completely assembled. This type of unit has the advantage of being adaptable to low-head installations.

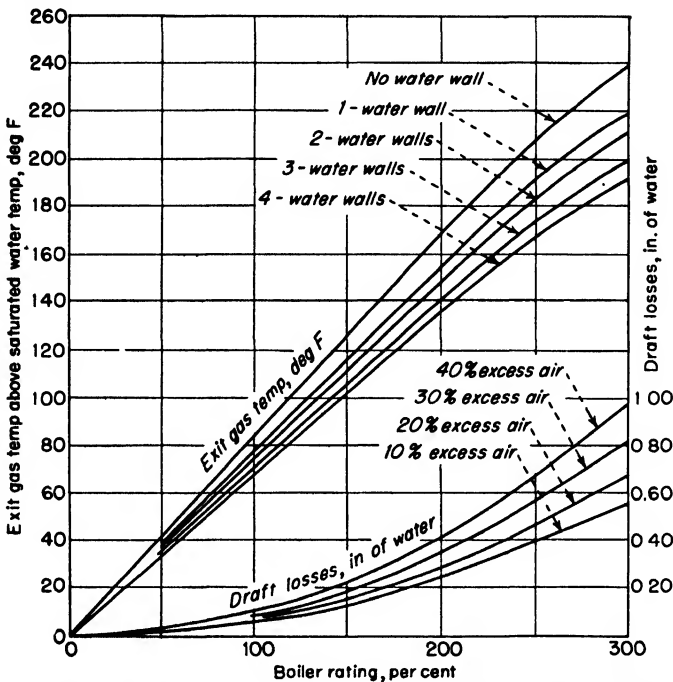


FIG. 21-34. Performance curves of three-drum boiler, oil-fired, set 12 ft.

**Four-drum Stirling Boiler.** The Stirling four-drum type was one of the earliest designs of bent-tube boilers extensively used, and it is still in active demand. This unit consists of a lower or mud drum, and three upper drums which are connected by water circulators and steam connectors (Fig. 21-35). All the drums of the front bank connect to the front drum, so that dissipation of the high-velocity discharge of the

**Table 21-11. Sizes and Capacities of Three-drum Boilers<sup>1</sup>**  
Some typical capacities of 100 to 1,000 hp for usual steam pressures and temperatures. Type 3-C<sup>1</sup>, standard sizes are given; any other required size can be made

No. of tubes wide..	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
Heating surface, sq ft	1,200	1,500	1,800	2,100	2,400	2,700	3,000	3,300	3,600	3,900	4,200	4,500	4,800	5,100	5,400	5,700	6,000
Furnace volume, cu ft	353	441	529	617	705	794	882	970	1,057	1,146	1,234	1,322	1,410	1,499	1,587	1,675	1,763
Diam of stack, in	30	30	36	36	42	42	42	48	48	48	54	54	54	60	60	60	60

NOTE: The characteristics of the type 3-C, the most popular model, are described here. Also available are the type 1-C, 2-C, and the 4-C. These differ from the 3-C in drum size and spacing.

<sup>1</sup> Erie City Iron Works.

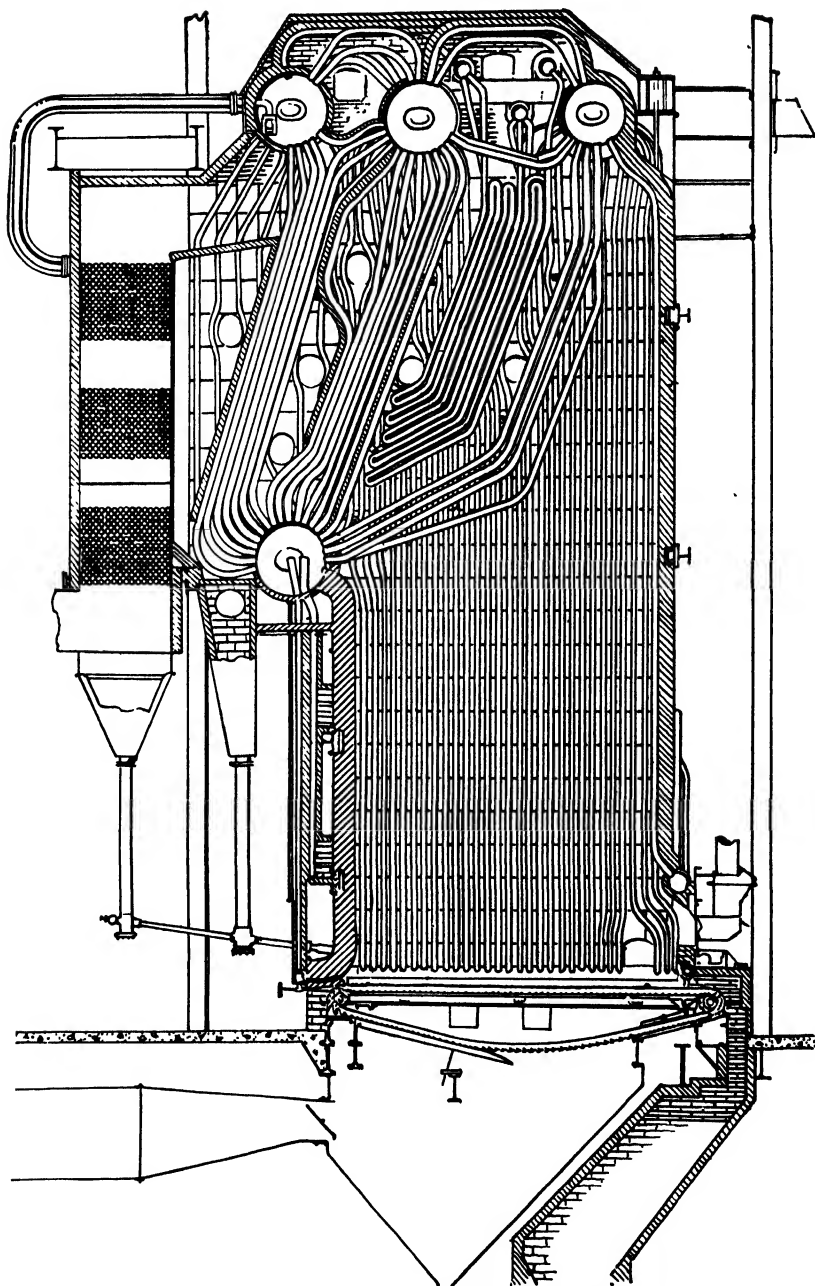


FIG. 21-35. Stirling boiler. (*The Babcock & Wilcox Co.*)

steam-and-water mix is confined to the front drum and is isolated from the steam discharge at the rear drum. In this first drum then, the initial separation takes place and a large portion of the water is removed from the steam. Additional separation occurs in the middle drum, and final separation occurs in the rear drum. The arrangement of the steam and water circulators governs the water level in the three upper drums—highest in the front drum, about half full in the middle drum, and lowest in the rear drum—to provide maximum steam space.

The basic design is flexible enough so that it is adaptable to a wide variety of furnace design. Any degree of furnace-water cooling—complete, partial, or none at

all—may be used, depending upon fuel characteristics, type of burning equipment, burning grates, load, and available space. Wide spacing of the front bank of tubes prevents bridging of slag between the tubes.

Experience has shown that the four-drum type can be operated at high capacity with a minimum of internal baffling. However, if the proper drum internals are used, the three upper drums may not be necessary for steam separation, and two upper drums are sufficient. Eliminating a drum results in less expensive construction. The units can be arranged for pulverized-coal firing, underfeed and spreader stokers, oil gaseous fuels, and wood or bagasse firing.

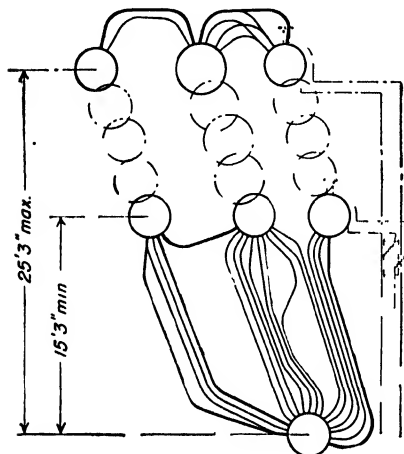


FIG. 21-36. Range of size of Stirling boilers. The availability of approximately 2,000 combinations of standard widths and cross sections of Stirling boilers assures the application of the one unit best suited to specific capacity and space conditions. The range of capacity is from 20,000 lb of steam per hour to 400,000 lb of steam per hour at top conditions of 950°F and 950 psi. (The Babcock & Wilcox Co.)

### HIGH-PRESSURE STEAM GENERATORS

High-pressure steam generators are by far most widely used in the modern central stations of the public utilities. They generally fall into two pressure classifications, 900 to 1,000 psi and 1,200 to 1,500 psi, these two ranges being

dictated largely by the turbine manufacturers. The steam temperatures range from 850 to 1050°F. Although these are the normal ranges, some units of large capacity (900,000 lb steam per hour) have recently been sold for operation at 2,000 psi and 1050°F. Provisions are usually made for maintaining constant temperature from maximum load down to some partial predetermined load. The units consist of completely water-cooled furnaces, large superheaters, a boiler convection bank, economizers in some cases, and large air heaters. The amount of convection surface depends on whether or not an economizer is used, the steam temperature desired, and the amount of steam-temperature control desired. If reheat cycle is employed, the basic furnace design may remain the same, but the relative location and disposition of superheater and economizer convection surface may vary considerably.

**Efficiency and Performance.** Small units operating at about 200 psi, with no heat traps such as air preheaters or economizers, are generally designed for efficiencies from 70 to 80 per cent.

Medium and large units are designed for efficiencies of 80 to 90 per cent. This efficiency depends on a number of factors such as first cost, type of fuel and firing,

cost of fuel, load factor, and boiler rating. Generally any one installation is sold for a specific performance that usually includes guarantees of maximum continuous capacity, efficiency or exit-gas temperature, steam quality, draft loss, and steam temperature to plus or minus 10° if a superheater is included.

### Special Steam-generator Forms<sup>1</sup>

The usual steam generators in common use are of conventional natural-circulation design using drums, tubes of large diameter, and headers. Boiler engineering here and in Europe has, however, concerned itself with changes in these basic designs to

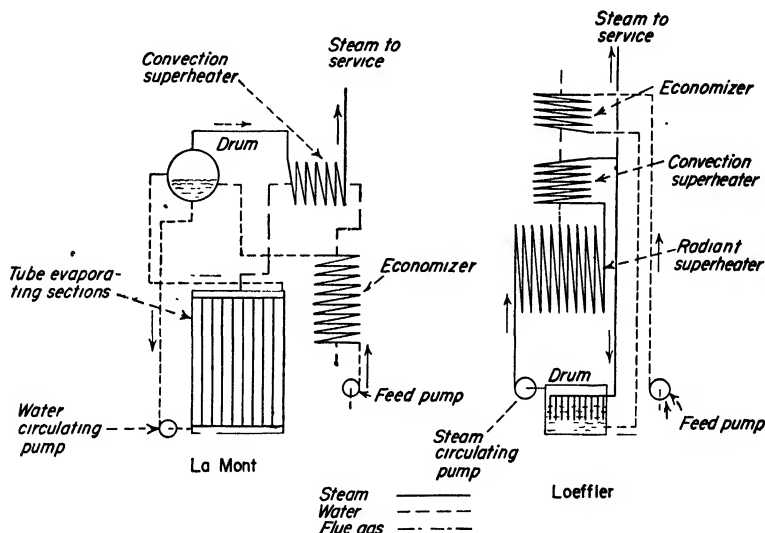


FIG. 21-37. Special boiler forms. (Applied Energy Conversion.)

produce better boilers in various respects. Foreign developments have been variously promoted by the ability to burn poor coal, the desire to lessen the quantity of steel used and lower the cost of field labor, extensive interconnections which lessen the importance of any one station, and the desire to use high-pressure steam.

Boilers that enter the category of a special type cannot be simply defined. In general, one or more of the following features tend to put a boiler in this class:

- |                    |                                    |
|--------------------|------------------------------------|
| Forced circulation | Pressure combustion                |
| Small tubes        | Multiple circuit                   |
| Lack of drums      | Extreme compactness and low weight |

The various important boilers that have been developed and built are indicated in the diagrammatic sketches of Figs. 21-37 to 21-39.

**La Mont Boiler.** This boiler or forms of it have been built here and abroad. It is a forced-circulation boiler using small-diameter tubes for the evaporating section. Orifices control the water flow to different evaporator sections. This permits various arrangements of the heat-transfer surface. The drum can be placed outside the furnace section. The boiler is very flexible in design owing to the forced circulation, and the small tubes make for a unit with high specific output. The design can be

<sup>1</sup> SKROTZKI, B. G. A., and W. A. VOPAT, "Applied Energy Conversion," pp. 312-315, McGraw-Hill Book Company, Inc., New York, 1945.

used for high or low pressures and various outputs and is the most used of the special boilers.

**Loeffler Boiler.** This unit has been designed to overcome feed-water troubles for high-pressure boilers. Feed water is passed through an economizer to a drum which is external to the steam generator. It is changed to saturated steam by allowing superheated steam to pass through it. The saturated steam formed flows to radiant and convection superheaters. Leaving here, it divides, about two-thirds going to the evaporator drum, and one-third to service. A turbine-driven steam pump is used to cause the flow of steam from the drum through the superheaters. To reduce pump work, the boiler is used only for high-pressure installations of about 2,000 psi. Small-bore tubes are used in the radiant section of the superheater. Concentrations of salts as high as 8,000 ppm have been handled in the evaporating drums. These drums lend themselves to easy cleaning.

**Benson Boiler.** This is a drumless boiler with continuous flow from feed pump to steam outlet. Water from the feed pump (Fig. 21-38) flows through the tube evapor-

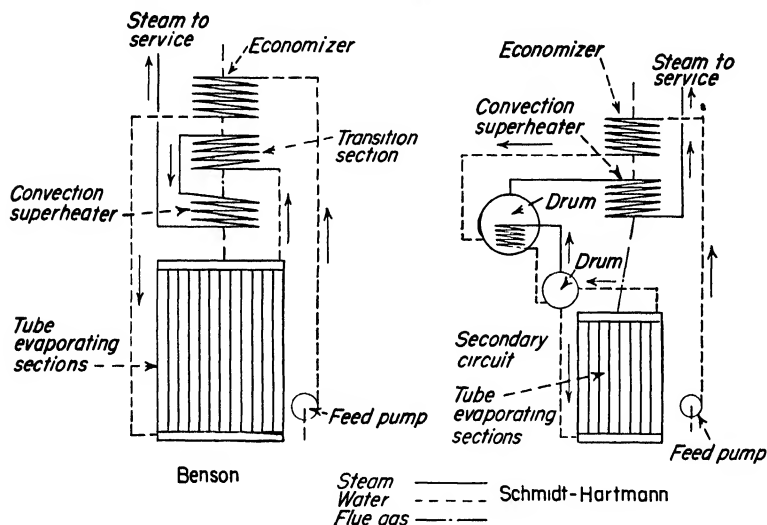


Fig. 21-38. Special boiler forms. (*Applied Energy Conversion*.)

ating sections where partial evaporation occurs. It is completed in the transition section, and superheated steam is formed in the convection superheater. The boiler is light in weight and forms a compact unit of high specific output. It can be started in some 15 min. This boiler was originally designed to operate at the critical pressure but is built for the range 400 to 3,300 psi and up to 990°F. They are extensively used in marine service.

**Schmidt-Hartmann Boiler.** This is a multiple-circuit boiler designed to overcome feed-water troubles. A feed pump discharges water to a drum from which steam flows to the superheater. Heating in the drum is done by steam from a secondary circuit. The heating elements in the drum resemble the headers and tubes of a sectional header boiler. The boiler has proved very effective in the formation of dry steam, and this is now its chief attribute. The boilers are built in pressure ranges of 500 to 1,800 psi and a variety of outputs.

**Velox Boiler.** This is a unit designed for pressure combustion giving high heat-transfer rates and low excess air. A pressure of about 35 psi is maintained in the

furnace owing to the use of compressed air for combustion. The air is compressed in an axial-flow air compressor driven by a gas turbine. The gas turbine operates from the high-pressure and high-temperature gases leaving the furnace. The boiler, though of small size, is highly efficient. It is built for pressure of 200 to 1,200 psi up to 950°F in a wide range of capacities. Most installations are in industrial plants, although some are used in central stations, marine work, and for locomotives. Many installations are for stand-by or emergency use.

**Ramsin Boiler.** This is a once-through boiler of Russian design. The elements of the tube evaporating section (Fig. 21-39) are inclined coils arranged in spiral forms making 40 parallel circuits which change to horizontal runs at the top. Steam, formed

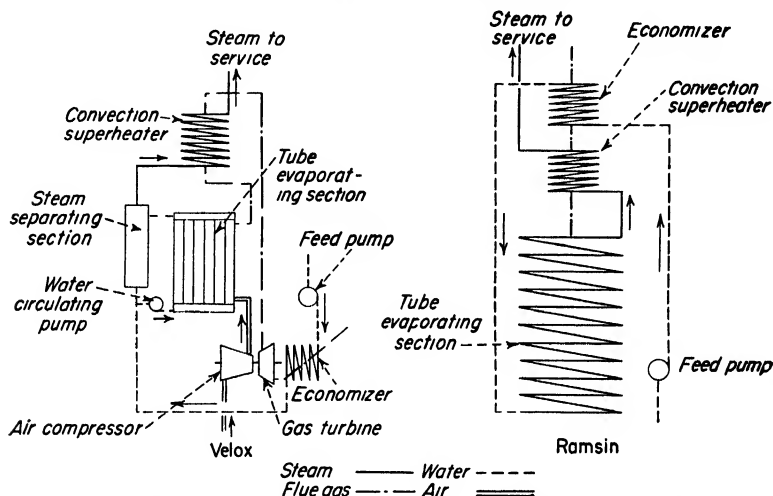


Fig. 21-39. Special boiler forms. (*Applied Energy Conversion.*)

in these circuits, passes to headers and then to the superheater. The boilers work at high and low pressure and are built in varying capacities.

## CYLINDRICAL FURNACES FOR THE PETROLEUM INDUSTRY<sup>1</sup>

The use of cylindrical furnaces for the petroleum industry has steadily increased since the advent of the original development by Luis de Florez for refinery use some 20 years ago. The future seems to offer still greater potentialities because of its simplicity and flexibility and because it can be built for substantially any duty, capacity, or efficiency. Its inherent design automatically provides more uniform heat distribution and absorption, low maintenance, low radiation losses, ease of cleaning, adaptability to heat-recovery equipment, less fire hazards, low space requirements, etc.

The original design of the de Florez was downfired, using cold forced air, a bottom convection section, and a natural-draft stack. Subsequent installations had many variations. Some were fired from the bottom with a secondary convection section on top. Some included air heaters and various combinations of forced- or induced-draft fans. The furnace and air heaters, both being vertical, produced a chimney effect and actually served as a part of the stack.

**De Florez Furnace.** The most successful design of the de Florez furnace, adopted as a standard by the Sinclair Refining Co., consists of (1) top-supported all-radiant oil-heating tubes, (2) downfiring with a specially designed directional flame-control

<sup>1</sup> CAMPBELL, O. F., "Cylindrical Furnaces for the Petroleum Industry," ASME Paper 49-SA-12, June, 1949.

oil and gas-fired burner, (3) a vertical refractory cone resting on the bottom of the furnace for better heat distribution, (4) a high-temperature Ljungstrom air heater, (5) forced- and induced-draft fans, and (6) a short self-supporting steel stack. This arrangement is shown in Fig. 21-40.

The **directional flame-control burner** handles refinery gas, natural gas, or heavy fuel oil. It is of the steam-atomizing type. It is specially designed to provide the desired flame shape, long and narrow, short and bushy, as desired. The flame can be shifted from one side of the furnace to the other to give the desired heating curve. Each 7-in. inside diameter air nozzle can supply enough air to burn between 10 and 15 million Btu per hr.

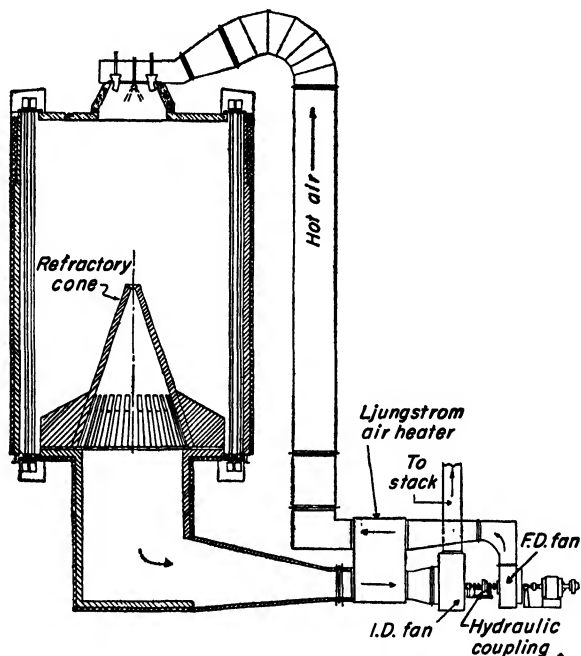


FIG. 21-40. Downdraft de Florez furnace equipped with Ljungstrom air heater.

The tube arrangement is very flexible in cylindrical furnaces. Arrangements can be made to give almost any required heating curve. Split-coil arrangements can be used to reduce pressure drop. The directional flame control can keep the highest heats away from parts of the tube banks as desired. Tube shields can also be used to keep too much heat from being absorbed at certain undesirable points.

With proper understanding of tube arrangement, flame control for heat distribution, refractory cone for better heat distribution and highly preheated air, the de Florez furnace can be designed for maximum heat absorption and maximum efficiency regardless of inlet- or outlet-oil temperatures.

**Iso-Flow Furnaces.** The Iso-Flow furnace, furnished by the Petro-Chem Development Co., New York, is also very popular because it is adaptable for small heat duties, and it is relatively cheap to build, requires small ground space, and has high efficiency for low-temperature stocks without the use of an air heater or fans. Campbell<sup>1</sup> feels that its greatest application is where the mean oil temperature is low.

<sup>1</sup> *Op. cit.*

The original design of the Iso-Flow furnace consisted of a vertical cylindrical shell of light sheet steel, insulated on the inside with insulating refractory or firebrick. Inside this insulated cylinder, bottom-supported vertical tubes were erected adjacent to the wall, burners were placed in a refractory well located at the bottom of the furnace, and the flue gases escaped from a stack placed on top of the furnace. There

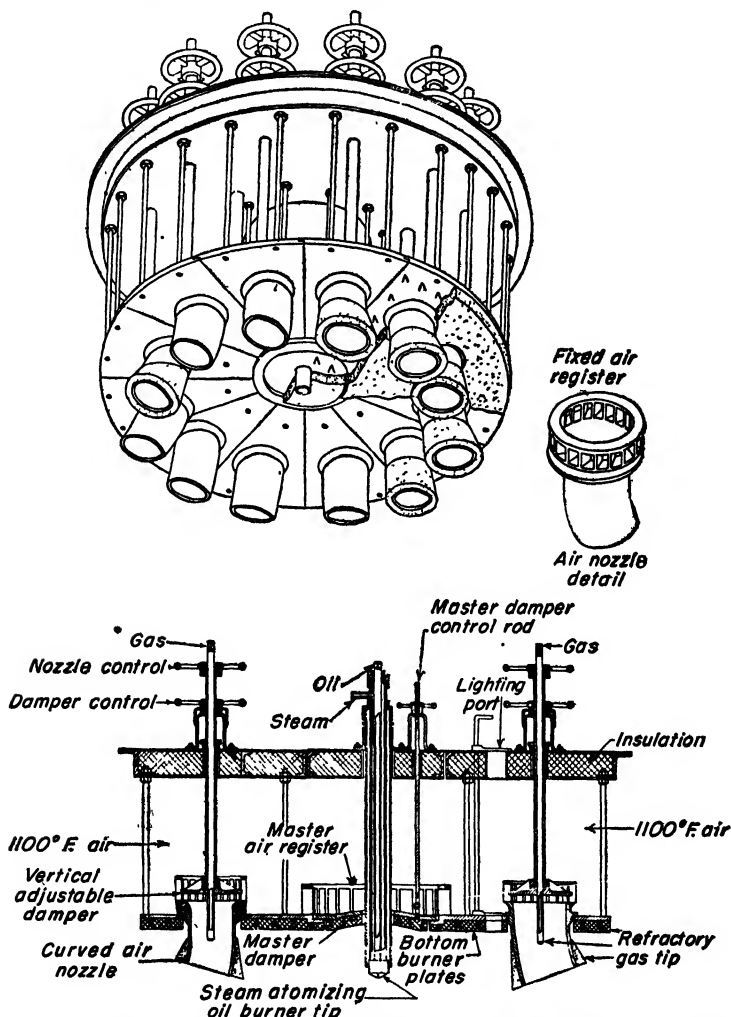


FIG. 21-41. Special burner used with downdraft de Florez furnaces and Ljungstrom air heaters. (Campbell.)

was suspended in the top of the furnace an alloy or refractory cone to radiate heat to the upper part of the tubes and to deflect the flue gases around the tubes in the upper part of the furnace. There have been many improvements and innovations over this original design.

In the **radiant-type Iso-Flow** furnace, the original firing well at the bottom has been eliminated and five John Zink burners installed in the bottom in such a manner that



the four on the outside give direction to the fire and distribution of heat to the tubes. The upper throat of the furnace is made of refractory. The efficiency is dependent upon the excess air in the furnace, average temperature of the stock inside the tubes, and the heat-absorption rate. This type of furnace is usually used where low cost of installation is required and low-priced fuel is available (Fig. 21-42).

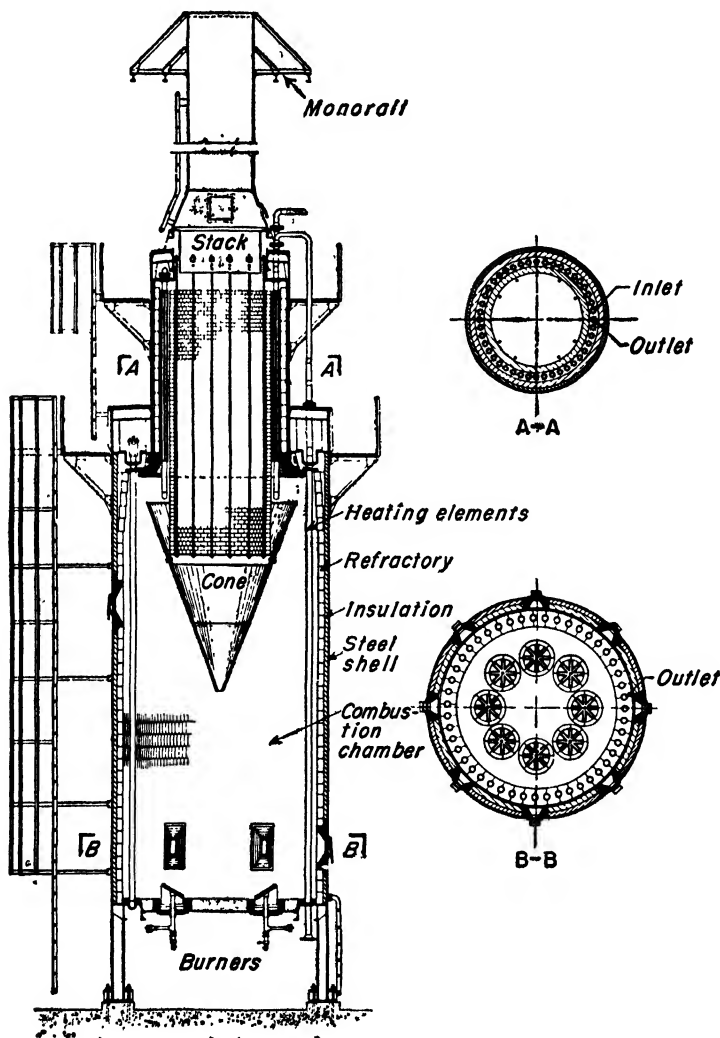


FIG. 21-42. Iso-Flow furnace with separate convection section. (Petro-chem Development Company.)

The radiant-convection type Iso-Flow furnace is substantially the same except that the radiant cone is suspended from a hollow cylinder inserted at the top of the furnace. Tubes are provided to constitute a convection section for further heat recovery. This type is usually used where fuel economy is desirable.

With an average temperature of approximately 450°F of oil in the tubes, the

efficiency of the radiant-convective type for a heat-absorption rate, based on tube surface only, of 8,000 to 10,000 Btu/sq ft/hr is approximately 70 to 72 per cent.

Air heaters can be installed in Iso-Flow furnaces for greater economy and greater heat-absorption rates, per square foot of tube surface. Various types of economizers, superheaters, etc., can also be employed advantageously.

**Iso-Flow Steam Boilers.** The application of the cylindrical furnace to a steam boiler is another innovation of the Petro-Chem Development Co. One which has been in operation for several years consists of a horizontal drum located above the furnace into which the furnace tubes deliver the water-steam mixture. A second design employs a vertical steam drum instead of the conventional horizontal. The steam and water mixture from the fired boiler tubes enters the vertical drum horizontally where it is given a rotary motion by baffling. As this separates the steam, the steam-liberating surface is a hollow cylinder of water in the vertical plane around the circumference of the boiler drum, which becomes a vertical centrifugal separator. Four such boilers are in operation (1949) designed for 400 psig and 30 to 50 thousand lb steam per hr. A separately fired superheater is used when desired. The immediate fuel is oil and gas, with adaptability to pulverized coal.

**Helical-coil Furnaces.** Helical-coil furnaces have many applications ranging from domestic hot-water heaters to the heating of oil stocks where the heat-absorption rate may be as high as 20 million Btu per hr. Their use is limited to applications where there is little or no likelihood that the tubes will plug. One application is the heating of asphalt at the point of loading so that it may be taken directly from the cars at the point of delivery without reheating. (Hot asphalt may be transported as far as 1,000 miles without cooling off to the extent that it will have to be heated for unloading.) The helical-coil furnace is usually limited to part-time operations, cheap fuels, and low-first-cost applications. This is by reason of inefficiency and danger of plugging.



## CHAPTER 22

### FUNDAMENTALS OF FURNACE DESIGN

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## GENERAL REQUIREMENTS FOR FURNACES<sup>1</sup>

A furnace is any chamber in which a fuel is burned, whether gaseous, liquid, or solid; and the burning must be accomplished so that complete combustion occurs. In addition, as in water-cooled furnaces, the heat-absorbing characteristics must be so designed that an optimum amount of heat is absorbed. In boilers or steam generators, the furnace is within the structure of the unit.

In general, design requirements are:

1. Suitable openings must be provided for the introduction of the fuel and air, but they must not permit air leakage.
2. Furnace dimensions should be of such a nature as to permit sufficient space for combustion equipment such as burners for liquid, gas, or oil, or for stokers.
3. Impingement of the flame on any part of the furnace should be avoided.
4. Combustion and temperature conditions in the furnace should be such that no deposit of slag in the furnace occurs, unless the design requires it to be deposited. Where the slag is deliberately deposited, the furnace construction must be impervious to it.
5. Wall construction should meet the following requirements:
  - a. The design and material of the furnace lining should be resistant to expansions and contractions due to temperature changes, temperature gradients, and load changes. Joints between the walls and floor should also be so resistant.
  - b. Insulation of the furnace should be provided to prevent heat losses.
  - c. Construction should be such as to prevent air leakage into the furnace with minimum maintenance.
  - d. Sufficient strength should be designed into the walls so that they are proof against failure in case of puffs within the furnace.
6. Where water walls are used:
  - a. The design should provide for adequate circulation and the prevention of short-circuiting of the fluid streams.
  - b. Water-wall headers should be outside of the furnace, as the thicker sections of the header are more likely to burn out if exposed to the flame.
7. The furnace dimensions should be adequate to permit complete combustion of the fuel in the furnace as designed.
8. Passages must be provided for the proper transporting of the products of combustion from the furnace before temperatures are reduced to a point where flow is inhibited.
9. Means must be provided for the elimination of fly ash, ashes, or slag formed and deposited in the furnace.
10. Adequate doors should be provided for access, inspection, and lancing.

## FURNACE TEMPERATURE<sup>2</sup>

The purpose of placing water tubes on the wall enclosure of a furnace is either to reduce the temperature of the gas and entrained ash so that the ash will be chilled below its softening temperature and consequently will not adhere to furnace or boiler

<sup>1</sup> KERRICK, J. H., Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa.

<sup>2</sup> CRAIG, O., "Furnace Design Methods, with or without Waterwalls," Midwest Power Conference, Riley Stoker Corp., Worcester, Mass., 1948.

surface, or to reduce furnace maintenance. If, for example, pulverized coal is burned in suspension in a furnace, the temperature of the gases and ash leaving the furnace and passing into the tube bank should be less than the fusion temperature of the ash, or the temperature at which ash will stick to the boiler tubes. If sufficient amount of water-cooling tubes is placed on the enclosure walls of the furnace, to absorb sufficient heat by radiation from the gases, the desired reduction in temperature will be obtained. In Fig. 22-1 are curves which provide a **reasonable guide** for determining the amount of water-cooled tube surface that may be required, or for determining the conditions of operation in an existing furnace with a particular coal so that slagging of ash may be avoided.

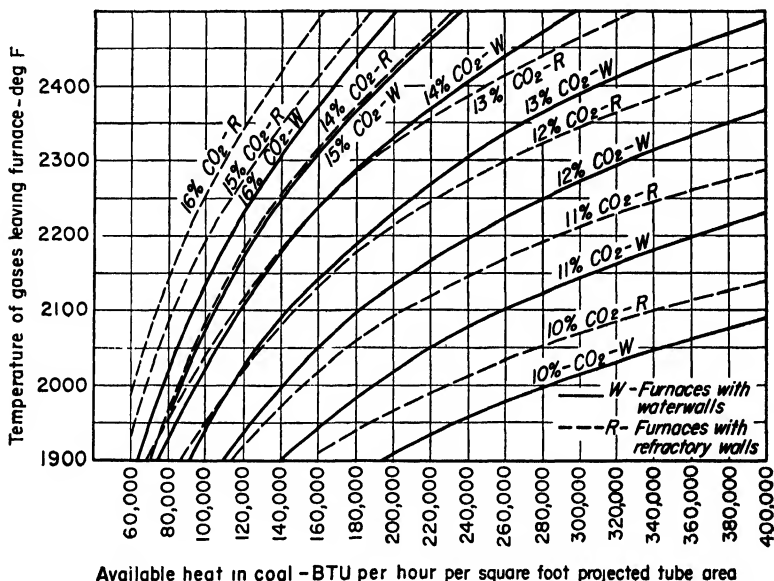


FIG. 22-1. Furnace-temperature curves. These curves will provide a reasonable guide for determining the amount of water-cooled surface required, or for determining the conditions of operation in an existing furnace with a particular coal so that slagging of ash may be avoided.

**Available heat** mentioned in Fig. 22-1 is that heat which either is or can be radiated to surrounding surfaces or remain as sensible heat in the products of combustion.

The **tubes** referred to are bare tubes, so placed as to be exposed to the furnace and subject to radiation from the furnace. It is the projected area of the tube that must be made use of, and not the circumferential area.

The **total projected area**, for use with the curves, is the sum of the projected area of the tubes on the furnace walls plus the projected area of the furnace exit. The projected area of the furnace exit is the projected length of the tubes in this area multiplied by furnace width.

**Curve** is particularly applicable to **pulverized coal firing** and reasonably accurate with oil firing. There is considerable error in the use of these curves when a gas, such

as natural gas, is a fuel, but the necessity for water cooling is less in the case of gas firing than in the case of oil firing.

The curves will give reasonable results with furnaces equipped with spreader stokers and with traveling-grate stokers burning bituminous coal, the furnaces having no

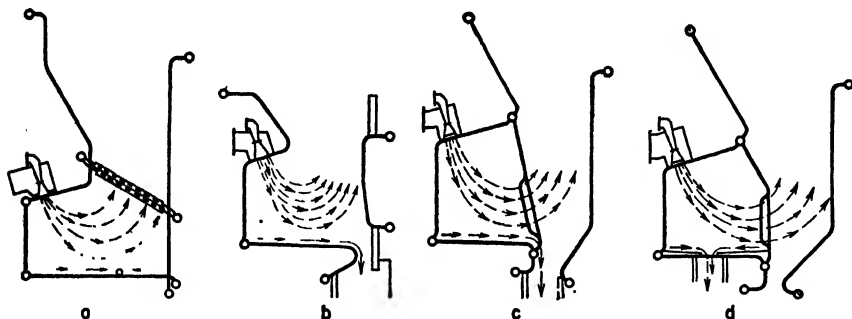


FIG. 22-2. Different ways of handling slag. *a.* Slag accumulates on the furnace floor and is tapped off periodically through a slag spout in the side wall. *b.* Slag drips continuously over the width of the floor at the rear of the furnace. *c.* Slag drains continuously between tubes of a slag screen at the rear of the primary furnace. *d.* Slag drains continuously through an opening in the floor of the primary furnace. (*The Babcock & Wilcox Co.*)

arches. Only approximate results can be obtained with other types of stoker installations. For this reason, see Tables 22-2 to 22-13 where reference is made to the term "fraction cold." This is a term frequently used in connection with single-retort stokers. "Fraction cold" is the ratio of the area of the water-tube surface exposed to a furnace to the total area of the furnace enclosure, exclusive of the area of the grate.

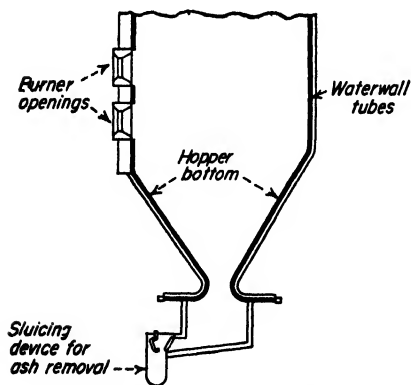


FIG. 22-3. Water-walled hopper bottom. Hopper is formed by bending water-wall tubes as shown. The slope of the tube is made greater than the ash angle of repose, so the bottom is self-cleaning. The ashes are sluiced out.

### FURNACE-DESIGN FACTORS<sup>1</sup>

The furnace enclosure which is exposed to the burning fuel can be entirely refractory with the exception of the tubes through which the gases pass when leaving the furnace. The furnace enclosure may be completely covered with water tubes through which water passes and is a part of the boiler circulating system. The furnace enclosure may be partly covered with water tubes, and the remaining area covered with refractory. The proportions of water-tube area and refractory vary widely, in the composite design.

The design of a furnace is very closely related to the kind of fuel to be burned and the means by which it is to be burned. In general, fuels are either burned on a grate or are burned in suspension. In Table 22-1 are shown the various furnace designs for the different types of fuel and methods of firing.

<sup>1</sup> CRAIG, O., *op cit.*

Table 22-1. Furnace Designs<sup>1</sup>

Fuel	Combustion type		Furnace	
	Suspension	Stoker or grate type	Walls	Bottoms
Gas .	Suspension	Underfeed, single or multiple retort. Spreader. Some traveling grates Most traveling grates	Usually vertical	Usually flat
Liquid ...	Suspension		Usually vertical	Usually flat
Solid .	Suspension		Usually vertical	Flat, with some form of liquid slag removal, see Fig. 24-2. Hopper, for large amounts of fly-ash precipitate in furnace, see Fig. 24-3
			Usually vertical	The stoker is actually the furnace bottom. Under the grate is usually some form of hopper for ash removal. In the smaller sizes the ashpit is flat and the ashes are raked out
			Side walls vertical. Rear or front wall (or both) projected over grate to form arch or roof. Arch or roof necessary for low-volatile fuels such as anthracite and coke breeze. Arch or roof probably necessary for high-moisture fuel such as lignite. Arch or roof can be omitted for bituminous provided gas turbulence is produced by overfire air jets. See Figs. 22-4 and 22-5	Same as underfeed stokers

<sup>1</sup> CRAIG, O., "Furnace Design Methods, with or without Waterwalls," Midwest Power Conference, Riley Stoker Corp., Worcester, Mass., 1948.

### Design for Various Classes of Equipment<sup>1</sup>

Tables 22-2 to 22-13, inclusive, show the salient design factors for the following classes of equipment:

Table 22-2: Single-retort stokers

Table 22-3: Multiple-retort stokers

Table 22-4: Traveling-grate stokers, anthracite burning

Table 22-5: Traveling-grate stokers, bituminous-coal burning

Table 22-6: Traveling-grate stokers, coke-breeze burning

Table 22-7: Traveling-grate stokers, lignite burning

Table 22-8: Spreader stokers, stationary grates

Table 22-9: Spreader stokers, dumping grates

Table 22-10: Spreader stokers, traveling grates

Table 22-11: Pulverized-coal firing

Table 22-12: Oil firing

Table 22-13: Gas firing

Sufficient information is given for an approximate check of fundamental furnace size or to determine the adequacy of existing installations. Items of furnace designs applicable to all types of equipment include the following:

<sup>1</sup> CRAIG, O.. *op. cit.*



1. Grate area
2. Furnace volume
3. Furnace height, grates to tubes
4. Rear-arch coverage
5. Front-arch coverage
6. Height of rear arch above grates

7. Height of front arch above grates
8. Furnace cooling
9. Length of furnace
10. Distance, burners to tubes
11. Distance, burners to furnace bottoms

While it is obvious that not every item listed above will apply to each type of firing equipment, this sequence has been used throughout with numbers merely omitted where the items do not apply.

**Table 22-2. Single-retort Stokers<sup>1</sup>**  
1. Grate Area

Furnace cooling, fraction cold	Lb coal/hr/sq ft* of stoker area at ash-fusion temp of	
	2200°F	2400°F
0.20	28	31
0.34	30	34

Based on 13 per cent CO<sub>2</sub> in gases leaving furnace.

**2. Furnace Volume**

Fraction cold	Btu in fuel/hr/cu ft at ash-fusion temp of	
	2200°F	2400°F
0.20	30,000	40,000
0.24	40,000	50,000
0.26	45,000	50,000
0.34	45,000	50,000

Based on 13 per cent CO<sub>2</sub> in gases leaving furnace.

**3. Furnace Height, Grates to Tubes**

$$\text{Avg furnace height} = \frac{\text{furnace volume}}{\text{grate area}}$$

<sup>1</sup> CRAIG, O., *op. cit.*

\* Coal-burning rates are for bituminous coal containing 10 per cent ash or less. If ash is 10 to 12 per cent, deduct 2 lb, if ash is 12 to 15 per cent, deduct 4 lb.

**Table 22-3. Multiple-retort Stokers**  
1. Grate Area

Stoker length, ft	Lb coal/hr/sq ft of stoker area at ash-fusion temp of	
	2200°F	2500°F
11	45	50
14	40	44.5
18		39.5

**Table 22-3. Multiple-retort Stokers.**  
(Continued)

**2. Furnace Volume**

Per Cent Volatile in Dry Coal	Btu in Fuel/Hr/Cu Ft of Furnace Volume
16	60,000
22	47,500
28	40,000
36	37,000
40	35,000

**3. Furnace Height**

Stoker Length, Ft	Distance from Grates to Tubes, Ft
11	14
18	22

**8. Furnace Cooling**

Ash-fusion Temp, Deg F	Btu in Fuel/Hr/Sq Ft Projected Tube Area
2100	140,000
2400	220,000
2600	360,000

Based on 14 per cent CO<sub>2</sub> in gases leaving furnace.

**Table 22-4. Traveling-grate Stokers, Anthracite Burning**

**1. Grate Area**

Size of anthracite	Btu in fuel/hr/sq ft of grate area		
	A	B	C
No. 4 buckwheat	450,000	400,000	350,000
No. 3 buckwheat	450,000	420,000	390,000
No. 2 buckwheat	470,000	470,000	470,000

A: Collection in back boiler passes, air-heater hoppers, and dust-collector hoppers returned to furnace for reburning.

B: Collection in back boiler passes and air-heater hoppers returned for reburning.

C: No collection returns.

**2. Furnace Volume**

Size of anthracite	Btu in fuel/hr/cu ft of furnace volume at burning rates in Btu/sq ft/hr		
	470,000	450,000	300,000
No. 4 buckwheat	.....	39,000	33,000
No. 3 buckwheat	.....	44,500	39,000
No. 2 buckwheat	.....	47,500	42,000

**Table 22-4. Traveling-grate Stokers, Anthracite Burning. (Continued)**

3. Furnace Height	
Continuous Capacity of Boiler, Lb Steam/Hr	Distance from Grates to Tubes, Ft
25,000	12.5
200,000	40 0

**4. Rear-arch Coverage**

Stoker length, ft	Per cent of stoker length covered by rear arch	
	Single-arch design	Double-arch design
14	60	55
24	..	57.5
28	67	

**5. Front-arch Coverage**

Stoker Length, Ft	Per Cent of Stoker Length Covered by Front Arch, Double-arch Design
14	25
24	20

**6. Height of Rear Arch above Grates**

Continuous capacity of boiler, lb steam/hr	Height of arches above Stoker grate			
	Single-arch design		Double-arch design	
	Front end	Rear end	Front end	Rear end
50,000	3'0"	2'0"	3'0"	2'0"
200,000	4'3"	2'6"	4'3"	2'6"

**7. Height of Front Arch above Grates**

Front arches approximately 8 ft 6 in. above stoker grates for all capacities.

**8. Furnace Cooling**

Ash-fusion temperature is less a factor in anthracite burning than in burning bituminous coal. Furnace cooling is primarily for reduction in maintenance. The Btu in fuel fired per hour should be from 180,000 to 300,000 per square foot of projected tube area. Lower rates are permissible, but higher rates result in less carbon loss.

**Table 22-5. Traveling-grate Stokers, Bituminous-coal Burning**

1. Grate Area	
Ash-fusion Temp, Deg F	Btu in Fuel/Hr/Sq Ft Grate Area
1900	425,000
2200 and above	550,000

2. Furnace Volume	
Btu in Fuel/Hr/Sq Ft of Grate Area	Btu in Fuel/Hr/Cu Ft of Furnace Volume
300,000	30,000
500,000	35,000

**Table 22-5. Traveling-grate Stokers, Bituminous-coal Burning. (Continued)**

3. Furnace Height, Grates to Tubes	
Continuous Capacity of Boiler, Lb Steam/Hr	Distance from Grates to Tubes, Ft
25,000	15
150,000	35

**4. Rear-arch Coverage**

30 to 40 per cent of stoker length.

**5. Front-arch Coverage**

30 to 20 per cent of stoker length.

**6 and 7. Height of Arches**

Continuous capacity of boiler, lb steam/hr	Height of arches above stoker grate		
	Rear arch		Front arch
	Rear end	Front end	
50,000	2'0"	2'3"	5'0"
150,000	2'0"	3'6"	6'0"

**8. Furnace Cooling**

Ash-fusion Temp, Deg F	Btu in Fuel/Hr/Sq Ft Projected Tube Area
1900	140,000
2200	180,000

**Table 22-6. Traveling-grate Stokers, Coke-breeze Burning****1. Grate Area**

Conditions of Operation	Btu in Fuel/Hr/Sq Ft of Grate Area
A	410,000
B	370,000
C	360,000

A: Collection in back boiler passes, air-heater hoppers, and dust collectors returned to furnace for reburning.

B: Collection in back boiler passes and air-heater hoppers returned for reburning.

C: No collection returns.

**2. Furnace Volume**

Btu in Fuel/Hr/Sq Ft of Grate Area	Btu in Fuel/Hr/Cu Ft of Furnace Volume
360,000	38,000
410,000	40,000

**3. Furnace Height, Grates to Tubes**

Continuous Capacity of Boiler, Lb Steam/Hr	Distance from Grates to Tubes
25,000	12'6"
200,000	40'0"

**4. Rear-arch Coverage**

Stoker Length, ft	Per cent of stoker covered by rear arch	
	Single-arch design	Double-arch design
14	60	55
24	..	
28	67	57.5

**Table 22-6. Traveling-grate Stokers, Coke-breeze Burning. (Continued)**

<b>5. Front-arch Coverage</b>		
<i>Stoker Length, Ft</i>	<i>Per Cent of Stoker Length Covered by Front Arch, Double-arch Design</i>	
14	25	
24	20	
<b>6 and 7. Arch Heights</b>		
Same as for anthracite.		
<b>8. Furnace Cooling</b>		
<i>Ash-fusion Temp, Deg F</i>	<i>Btu in Fuel/Hr/Sq Ft Projected Tube Area</i>	
2100	100,000	
2400	200,000	

**Table 22-7. Traveling-grate Stokers, Lignite Burning**

<b>1. Grate Area</b>	
Type of	Btu in Fuel/Hr/Sq Ft of Grate
Furnace Walls	Area
All refractory	400,000
Water-cooled	450,000
<b>2. Furnace Volume</b>	
Type of	Btu in Fuel/Hr/Cu Ft Furnace
Furnace Walls	Volume
All refractory	30,000
Water-cooled	35,000
<b>3. Furnace Height</b>	
Continuous Capacity	Distance from Grates to
of Boiler, Lb Steam/Hr	Tubes, Ft
50,000	22
150,000	30
<b>4. Rear-arch Coverage</b>	
30 per cent of stoker length.	
<b>5. Front-arch Coverage</b>	
35 per cent of stoker length.	
<b>6. Height of Rear Arch above Grates</b>	
2 ft 0 in.	
<b>7. Height of Front Arch above Grates</b>	
Continuous Capacity of	Height of Arch above
Boiler, Lb Steam/Hr	Stoker Grate
50,000	4'3"
150,000	6'0"
<b>8. Furnace Cooling</b>	
Ash-fusion	Btu in Fuel/Hr/Sq Ft Pro-
Temp, Deg F	jected Tube Area
2100	140,000
2400	220,000

**Table 22-8. Spreader Stokers, Stationary Grates**

<b>1. Grate Area</b>		
	<i>Btu in fuel/hr/sq ft of grate area</i>	
	<i>With dust collector</i>	<i>Without dust collector</i>
Max continuous load	400,000	350,000
2 hr peak load	450,000	400,000

**Table 22-8. Spreader Stokers, Stationary Grates. (Continued)**

<b>2. Furnace Volume</b>		
	<i>Btu in fuel/hr/cu ft of furnace volume</i>	
	<i>Refractory furnace</i>	<i>Water-cooled furnace</i>
Max continuous load	30,000	30,000
2 hr peak load	35,000	40,000

**3. Furnace Height, Grates to Tubes**

$$\text{Height from grates to tubes} = \frac{\text{furnace volume}}{\text{grate area}}$$

Minimum heights desirable:

	<i>Ft</i>
Eastern coals	12
Middle Western coals	14
Lignite	15

**8. Furnace Cooling**Calculated from curves of Fig. 22-1 on basis of 14 per cent CO<sub>2</sub> in gases leaving furnace.**Table 22-9. Spreader Stoker, Dumping Grates**

<b>1. Grate Area</b>		
	<i>Btu/hr/sq ft of grate area</i>	
	<i>With dust collector</i>	<i>Without dust collector</i>
Max continuous load	475,000	375,000
2 hr peak load	525,000	450,000

**2. Furnace Volume**

Same as stationary grates.

**3. Furnace Height, Grates to Tubes**

Same as stationary grates.

**8. Furnace Cooling**

Same as stationary grates.

**Table 22-10. Spreader Stokers, Traveling Grates**

<b>1. Grate Area</b>			
	<i>Btu in fuel/hr/sq ft of grate area at continuous boiler capacities, lb/hr</i>		
	100,000	200,000	300,000
Max continuous load	575,000	650,000	725,000
2 hr peak load	650,000	700,000	750,000

**Table 22-10. Spreader Stokers, Traveling Grates. (Continued)**  
2. Furnace Volume

	Btu in fuel/hr/cu ft furnace volume	
	Refractory furnace	Water-cooled furnace
Max continuous load . .	30,000	30,000
2 hr peak load . .	35,000	40,000

### 3. Furnace Height, Grates to Tubes

Same as stationary grates.

### 8. Furnace Cooling

Same as stationary grates, but with 15 per cent CO<sub>2</sub> in gases leaving furnace.

**Table 22-11. Pulverized-coal Firing**  
2. Furnace Volume

	Btu in fuel/hr/cu ft of furnace volume	
With ash-fusion temp of . . . . .	1900°F	2400°F
Furnace all refractory . . . . .	8,500	17,000
Furnace partly water-cooled . . . . .	10,600	19,000
Furnace, air-cooled suspended refractory with hopper bottom . . . . .	13,600	22,000
Furnace, completely water-cooled with hopper bottom . . . . .	7,600	26,000

### 8. Furnace Cooling

Use curves of Fig. 24-1.

### 9. Length of Furnace

Max Continuous Boiler Capacity, Lb Steam/Hr	Length of Furnace from Front to Area at Burner Line, Ft
50,000	14
500,000	23

### 10 and 11. Placement of Burners in Furnace Wall

Type of Furnace Bottoms	Per Cent of Furnace Volume Below Line of Burners
Flat bottom . . . . .	45
Hopper bottom: . . . . .	
With boiler capacity of 100,000 lb steam/hr . . . . .	35
With boiler capacity of 500,000 lb steam/hr . . . . .	25

**Table 22-12. Oil Firing**  
2 and 8. Furnace Volume and Furnace Cooling

Max continuous boiler capacity, lb steam/hr	Btu in fuel/cu ft furnace volume with available Btu in fuel/hr/sq ft of projected tube area of		
	80,000	200,000	300,000
30,000	33,000	28,000	18,000
100,000	36,500	31,500	23,000
300,000 and over	40,000	35,000	27,000

### 9. Length of Furnace

Max Continuous Boiler Capacity, Lb Steam/Hr	Length of furnace
50,000	10'9"
100,000	13'6"
200,000	16'9"
300,000	18'0"
600,000	20'0"

### 10. Distance, Burner to Tubes

Max Continuous Boiler Capacity, Lb Steam/Hr	Distance from Center Line of Burners to Tubes
50,000	12'0"
100,000	14'6"
200,000	20'0"
300,000	25'0"
600,000	30'0"

### 11. Distance, Burners to Bottom

Max Continuous Boiler Capacity, Lb Steam/Hr	Distance from Center Line of Lower Burners to Flat Furnace Floor
100,000	4'6"
600,000	6'6"

**Table 22-13. Gas Firing**

2 and 8. Furnace Volume and Furnace Cooling	
Available Btu in Fuel/Hr /Sq Ft of Projected Tube Area at Max Continuous Load on Boiler	Btu in Fuel/Hr/Cu Ft of Furnace Volume
100,000	35,000
300,000	35,000
400,000	27,000

### 9. Length of Furnace

Max Continuous Capacity of Boiler, Lb Steam/Hr	Length of Furnace
50,000	10'0"
400,000	20'0"
600,000	20'0"

### 10. Distance, Burners to Tubes

Max Continuous Capacity of Boiler, Lb Steam/Hr	Distance from Center Line of Burners to Tubes
50,000	12'6"
400,000	25'0"
600,000	30'0"

### 11. Distance, Burners to Furnace Bottoms

Same as oil firing.

Furnace-design Variations<sup>1</sup>

The design data given in Fig. 22-1 and Tables 22-2 to 22-13 are for standard arrangements of furnaces. There are many variations which require special treatment beyond the scope of the data given here.

**Pulverized Coal.** Most installations for pulverized coal have horizontal turbulent burners, hopper bottoms, gas outlets at the top of the furnace, and dry-ash discharge. The design data given are for this type of furnace. However, some furnaces are arranged with burners at the top of the furnace discharging downward, gas outlets

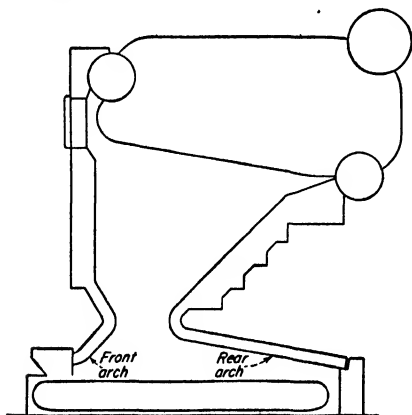


FIG. 22-4. Typical arches used for anthracite.

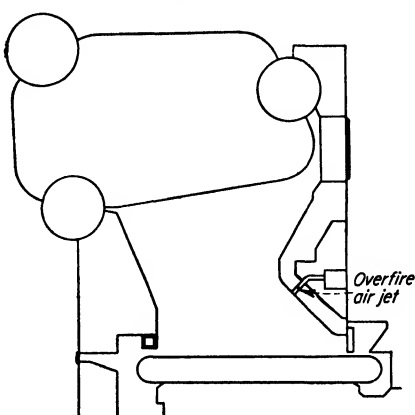


FIG. 22-5. Arch for bituminous coal, showing overfire air jet.

at the bottom of the furnace, and ash removal in a liquid form, or some combination of these. Such designs require special treatment.

**Stokers.** There are the most variations in furnace design with traveling-grate and chain-grate stokers because of the use of **arches**, or **roofs**. The **purpose of the arch** is twofold, to promote the ignition of the fuel, and to produce turbulence and mixing of the gases. A furnace may have a rear arch only, front arch only, both front and rear arches, or no arches at all.

An **arch** in a furnace over a traveling-grate or chain-grate stoker may promote ignition of incoming fuel by the projection of live coals on top of the fresh fuel or by radiation. Radiation may come from a hot surface on an arch or may come from flame. If arches are depended upon for ignition by radiation, the design of the rear arch is important since it must provide means for obtaining sufficient radiation to secure ignition. Because many rear arches are constructed with boiler tubes having water in circulation, it seems apparent that their function is to direct the flame so that radiation from the flame will produce ignition. The shape and proportion of this arch become quite important in order that it may give proper direction to the flame. Front arches over such stokers are probably of more importance in performing a function of producing turbulence and mixing of gases than in promoting ignition by radiation. Front arches may vary from horizontal to a very steep inclination of as much as 60 deg to the horizontal. The more nearly horizontal, the more effective such arches are in producing turbulence.

**Jets.** In the absence of arches, overfire jets (either steam jets or air jets) are necessary to provide both turbulence and ignition. In the case of furnaces without arches, there should be overfire jets both front and rear. The rear jets should be at a

<sup>1</sup> CRAIG, O., *op cit.*

Table 22-14. Traveling-grate-stoker Arch Design

<i>Fuel and Principal Type of Arch Recommended</i>	<i>Notes</i>
Anthracite:	
No. 3 buckwheat (barley), No. 4 buckwheat, rear arch	<ol style="list-style-type: none"> <li>1. For prompt ignition and stability, heat should be radiated from refractories to incoming fuel; incandescent fuel should be transferred from rear to incoming fuel; and high-temperature flame and gas should be in contact with incoming fuel</li> <li>2. Rear arch nearly horizontal with medium-length stokers; inclined with rear not too close or nose too high for large stokers (6 wind boxes or more)</li> <li>3. Arch-design data: 40 to 50 fps recommended gas velocity between grate and nose of rear arch; 25 to 35 fps between nose and front wall; 50 to 60 per cent of fuel burned under rear arch. Design constants, 2500°F, 15 per cent CO<sub>2</sub></li> <li>4. Barley efficiency likely to be 2 to 5 per cent higher than No. 4 buckwheat because of reduced carbon loss</li> <li>5. Fuel-bed depth 4 to 4½ in. with barley. Combustion rate 35 and 45 lb/sq ft/hr without and with cinder return</li> </ol>
No. 2 buckwheat (rice), rear or combination arch	<ol style="list-style-type: none"> <li>6. Unless a rear arch can cover at least 15 ft of the grate (for stable ignition), a combination arch is recommended. Three air zones should be covered by a rear arch with rice</li> </ol>
Coke breeze:	<ol style="list-style-type: none"> <li>7. Same requisites to prompt ignition and stability apply as for anthracite (see item 1)</li> <li>8. Water-cooled front and side walls usually advisable on account of lower fusion temperature of ash</li> </ol>
Size, ½ to ¾ in., rear arch	<ol style="list-style-type: none"> <li>9. Same as items 1, 2, 3, for anthracite, in addition to coke items 7 and 8</li> </ol>
Size ¾ to 1 in., front or combination arch	<ol style="list-style-type: none"> <li>10. Front-arch-type furnaces are usually used because of the heat-stabilizing effect</li> </ol>
Lignite, front or rear arch	<ol style="list-style-type: none"> <li>11. Front arch usually used for natural-draft chain-grate stokers. Combustion rate to about 30 lb/sq ft/hr. Arch covers as much as ¾ of grate. Slope about 25 deg. Lower end 2 to 2½ ft above grate. Burning rate to 75 lb with forced draft</li> <li>12. Excellent results also reported in rear-arch settings similar to those described for items 3 and 4</li> </ol>
Bituminous coal:	
1. Combination arch.	<ol style="list-style-type: none"> <li>13. Virtually all types of arch are used with bituminous according to such factors as fuel analysis, combustion rate, and furnace size. One of the most popular types is the combination arch similar to certain of the earlier designs for anthracite barley</li> <li>14. With combination arches and bituminous, both efficiencies and ratings are high which usually indicates the advisability of water-cooled furnace walls and preheated air. Otherwise refractory costs are likely to be high</li> </ol>
2. Rear arch.....	<ol style="list-style-type: none"> <li>15. Have been successfully used with low furnace maintenance with such bituminous coals as moderately caking Pittsburgh district, and Illinois screenings</li> <li>16. Rear arch and combination arches with bituminous usually result in a reduction in carbon loss in both carry-over and refuse as well as in better turbulence than does a front arch as used alone</li> </ol>
3. Archless.....	<ol style="list-style-type: none"> <li>17. Also known as "open" furnaces. Grate is virtually uncovered, with the possible exception of a short ignition arch</li> <li>18. Ignition is likely to be somewhat unstable especially if the load is at all fluctuating. This type is thus recommended for constant loads only. Overfire air is also needed in most cases to create turbulence and reduce stratification. With these limitations, good results have been reported</li> </ol>
Overfire air.....	<ol style="list-style-type: none"> <li>19. The use of secondary air is common practice when burning bituminous coal on traveling- or chain-grate stokers. While exact rules have not been established because of the many field conditions, the following are useful generalizations: <ol style="list-style-type: none"> <li>a. From 5 to 10 per cent of the air for combustion should be admitted as secondary air</li> <li>b. The best method for admission is probably through several jets having a pressure of from 20 to 30 in. Such jets are not effective below 6 in. water pressure</li> <li>c. Air introduced into a high-velocity gas stream is not so effective as when introduced into a low-velocity stream</li> <li>d. Location in the front arch or at the front of the furnace seems more effective in burning the gases than the rear</li> </ol> </li> </ol>

lower elevation than the front jets. The rear jets then take the place of a rear arch in that they force the flame toward the front and thereby provide more intense radiation from the flame onto the incoming fuel for ignition. The front jets take the place of the front arch, reversing the flow of gases in a horizontal direction and promoting turbulence. In any particular case, the number of jets, the diameter of the nozzles, the position of the nozzles, and the inclination of the nozzles and pressure of air, if overfire jets are used, are of extreme importance and must receive special consideration. The work done by the Bituminous Coal Research, Inc., and Battelle Institute has resulted in the most rational methods of application up to the present time. It is known that the use of overfire jets reduces carry-over of solids by the gases, but at the present time the knowledge in this respect is only general.

### SMALL OIL-FIRED FIREBOXES<sup>1</sup>

**Purpose.** Pressure burners, low-pressure gun-type burners, and horizontal rotary-cup burners—which are all of the atomizing type—operate satisfactorily and at maximum efficiency only when fitted with durable fireboxes that can quickly reach the high temperatures needed for complete combustion. The lack of a proper firebox in any boiler or furnace means inefficient combustion, frequent cleaning of the flues, breakdowns caused by poor burning, and high rates of fuel consumption.

With the trend toward shorter oil-burner on periods and smoother heating, it is important to ensure clean economical combustion by installing fireboxes which reach red heat quickly after the burners start. Running the oil burner with the firebox cold wastes fuel and forms carbon.

**Firebox Principles.** An inferior firebox will cause excessive oil consumption, flame vibration, and trouble because of failure to burn the fuel cleanly. A good design depends on:

1. Proper firebox material
2. Correct firebox design
3. Proper installation

Good firebox material has refractory properties that permit the construction of durable boxes which can quickly reach the high temperatures necessary for clean combustion.

For correct design, the firebox must be of the right size and shape. The firebox material should permit building boxes of widely varying shapes.

Proper installation is as important as selection of material and correct design.

### Firebox Design

The following points are important when modernizing an old installation or when engineering the installation of a new burner:

**1. Use rapid-heating firebox material.** The risk of forming smoke and soot comes mainly during the time when a cold firebox is being heated by the newly started flame. A properly designed firebox of insulating firebrick reaches red heat quickly after an oil burner starts. Because of the insulating quality of the brick, only a thin "skin" which faces the fire is heated during the first few minutes of burner operation, while the remainder of the brick remains comparatively cool.

**2. Design a flame-fitting firebox.** Make the firebox as small as is practical for the gph (gallons per hour) rate to be used by following the instructions for firebox proportions shown in Tables 22-15 and 22-16. Have the firebox fit snugly the flame shape the particular burner tends to give. Many burners operate at maximum combustion efficiency only when giving a flame of some certain shape, and for these burners a

<sup>1</sup> B&W Firebox Handbook, Bull. R-20B, Babcock & Wilcox Co., Refractories Division, New York, 1948.

firebox tailored to this shape should be built wherever the contour of the furnace or boiler base permits.

**3. Make the firebox high.** Make the side walls at least as high as indicated by the firebox-dimension tables. Do not hesitate to have the firebox walls cover some of the direct heating surface in the boiler or furnace if high side walls are needed to

**Table 22-15. Typical Firebox Dimensions for Domestic Oil Burners<sup>1</sup>**

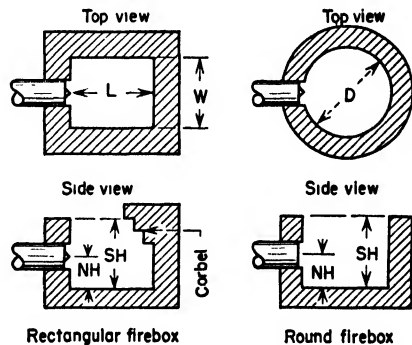
Gph	Normal flame shapes					Narrow flames				Wide flames				Gph
	Nozzle height <i>NH</i>	Side height <i>SH</i>	Rectangular		Round, diam <i>D</i>	Nozzle height <i>NH</i>	Side height <i>SH</i>	Width <i>W</i>	Length <i>L</i>	Nozzle height <i>NH</i>	Side height <i>SH</i>	Width <i>W</i>	Length <i>L</i>	
			Width <i>W</i>	Length <i>L</i>										
1 0	6	14	10½	12	12	6	14	9½	14	7	16	13½	10	1 0
1.3	6	16	11¼	13½	13½	6	14	10½	16	7½	17	15½	11	1 3
1 7	6½	16	12	15	15	6	16	11½	18	7½	17	17	12	1 7
2 0	6½	16	13	16	16½	6½	16	12¼	20	8	18	19	13½	2 0
2 5	7	16	14	17	18	6½	16	13½	22	8	18	21½	15	2 5
3 0	7	18	16	19	20	6½	16	14	24	8½	19	23½	16½	3 0
4 0	7½	18	17½	20½	23	7	18	15	27	9	20	26	18	3 5
5 0	7½	18	19	22	26	7	18	16½	30	9½	21	28	19½	4 0

<sup>1</sup> B&W Firebox Handbook, Bull. R-20B, Babcock & Wilcox Co., Refractories Division, New York, 1948.

produce high CO<sub>2</sub> readings and complete combustion. High side walls give improved air circulation in certain warm-air furnaces and improved water circulation in certain gravity-flow hot-water-heating plants. Also, they protect the water legs (where sediment, rust, or mud may collect) of steam boilers from excessive heat.

**4. Make good use of corbel design.** Stepped-in walls or corbels, for at least the back of the firebox and sometimes for the front walls also, are decidedly advantageous where exceptionally high CO<sub>2</sub> readings and smoke-free soot-free combustion are desired from burners with only ordinary air-handling parts at the ends of the gun tubes. Many burner dealers use front-wall and rear-wall corbels for their smallest installations, fired at 1 gph or less. Corbels (Fig. 22-6) greatly increase the turbulence of the flames, thus preventing unburned oil or carbon from escaping from the firebox. Corbels also increase the flame temperatures by reducing the flow of radiant heat from the heart of the flame to the direct heating surface of the boiler or furnace.

**5. Aim for nearly steady burner operation.** Because unnecessary starting and stopping wastes fuel and forms carbon in a burner, engineer each installation to keep the burner running as steadily as feasible on the coldest days. Use the lowest gph rate on each installation which will heat the house properly for the coldest mornings. Where the cycles must be short, it is necessary to use insulating firebrick for firebox construction for rapid heating.



**FIG. 22-6. Firebox dimensions, used with Table 22-14.**



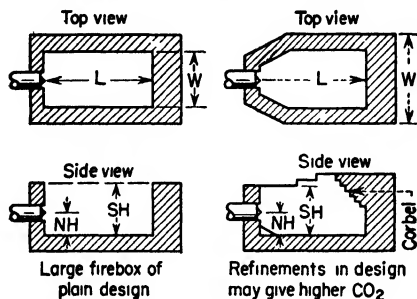
### Firebox Dimensions

If the manufacturer of the burner being installed issues instructions for building fireboxes of insulating firebrick, these should be followed so that the firebox will match the flame shape. If these are not available, use the following tables.

Where the shape of the boiler or furnace base permits, always make the firebox fit the flame shape. Table 22-16 covers fireboxes which match the flame shape of many pressure burners. Where the ashpit shape forces a design which is a very narrow or very short firebox, fit the flame shape to the firebox by:

1. Using either a narrow-angle or a wide-angle nozzle in a pressure burner.
2. Making use of any air-handling parts at the end of the gun tube that can be adjusted or changed to fit the flame to the firebox shape.

**Table 22-16. Firebox Dimensions for Commercial Installations<sup>1</sup>**



(All dimensions in inches)

Gph	Nozzle height NH	Side height SH	Width W	Length L	Sq in. of firebox floor area required*
6 0	8	20	20	26½	520- 540
7 0	8½	20	21	29½	610- 630
8 0	9	21	22	32	695- 715
9 0	9	22	24	33	775- 795
10 0	10	22	24½	35	850- 870
11 0	10	24	26	36	920 940
12 0	11	24	27	37	985- 1,005
13 0	12	24	28	38	1,045- 1,065
14 0	12	24	28½	39	1,100 1,120
15 0	13	26	28½	40½	1,140- 1,160

<sup>1</sup> B&W Firebox Handbook, Bull. R-20B, Babcock & Wilcox Co., Refractories Division, New York, 1948.

\* If for any reason the listed firebox width and length do not fit the base of the boiler, use dimensions which give the floor area listed for the required gph rates. If a considerable change from the table figures for width or length must be made, resulting in the firebox fitting the flame shape poorly, provide 10 to 25 per cent more floor area than the table lists. Protect the mud leg of a dry-base boiler from excessive heat by making the side walls of a firebox at least 4 in. higher than the bottom of the water leg of the boiler.

### Furnace Proportions of Commercial Steel Boilers

Furnace proportions, such as grate area, furnace volume, and furnace height for mechanically fired and hand-fired commercial steel boilers are found in Chap. 21, under the Rating Code of the Steel Boiler Institute (p. 715).

## CHAPTER 23

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### METHODS OF FIRING SOLID FUELS

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Table 23-1. Capacity Range of Equipment for Burning Various Fuels

Fuel	Equipment available	Max burning rate No./sq ft per hr	Approximate range of capacities available (pounds of steam per hr.)				
			0	10 M	20 M	30 M	40 M
Anthracite	Hand-fired grates	20	0 to 20,000				
	Semistokers (McClave)	23 (a)	2,000 to 20,000				
Caking bituminous	Single-retort (Skelly)	20 (b)	1,000 to 7,500				
	Traveling-grates (Hazleton)	25 (c)	850 to 8,500				
	Traveling-grates, large	40	15,000 to 200,000				200 M
	Pulverized coal		35,000 to 1,000,000				200 M
Free-burning bituminous	Hand-fired grates	20	0 to 20,000				
	Single-retort, underfeed	30 (d)	15,000 to 40,000				
	Multiple-retort, underfeed	35	15,000 to 200,000				200 M
	Spreaders, dumping	40	1,000 to 125,000				125 M
	Spreaders, continuous discharge	40	15,000 to 200,000				200 M
Subbituminous	Traveling-grates	40	15,000 to 200,000				200 M
	Pulverized coal		35,000 to 1,000,000				1 MM
Lignite	Hand-fired grates	15	0 to 15,000				
	Spreader	50	15,000 to 275,000				275 M
	Traveling-grates	50	15,000 to 275,000				275 M
Coke breeze	Pulverizers	50	35,000 to 1,000,000				1 MM
	Hand-fired grates	18	0 to 17,500				
Notes	Spreader	50	15,000 to 275,000				275 M
	Traveling-grates	50	15,000 to 275,000				275 M
Coke breeze	Pulverized coal		35,000 to 1,000,000				1 MM
	Traveling-grates	30	15,000 to 150,000				150 M
a - Also called "hand-stokers"			b - To 1,050 lb coal/hr				
c - 25 to 250 hp			d - Spreaders preferred for high-ash, low fusion coal				

Table 23-2. Principal Types of Equipment Available for Burning Anthracite<sup>1</sup>

Class of equipment	Typical manufacturers	Description of equipment, sizes and uses	Characteristics of coal		
			Optimum coal size (numbers refer to order of choice)	Desirable coal properties	Undesirable coal properties
Domestic Heating Equipment					
Domestic hand-firing	Various	Hand-fired steam and hot-water boilers, warm-air furnaces, space heaters, ranges, water heaters, etc. This type of equipment consumes more than $\frac{1}{2}$ of the total production of anthracite	Depends on the size and type of equipment	Nonclinking low ash, reasonably uniform sizing	High ash, excessive fines, low fusion except at low combustion rates
Magazine feed boilers	Spencer Heater Co., Williamsport, Pa.	Various sizes with magazine capacities from 100 to 1,650 lb. coal and outputs (E.D.R., steam) 175 to 4,500 ft.	1. No. 1 buckwheat 2. Pea	Uniform size, nonclinking, high shrinkage, moderate H <sub>2</sub> O to minimize arching	Clinker or high ash prevents proper coal feed from magazine
Domestic underfeed stokers	Various	Sizes to approx 90 lb/hr (2,600 sq ft E.D.R.) on No. 1 buckwheat. Some models can use rice, usually with 10 to 20 % less output and to 75 lb/hr	1. No. 1 buckwheat 2. Rice	Ash fusion above 2750°F. Sizing very important. Coal must be well screened	Some will burn mildly clinking coal, but not if low in ash fusion
Reciprocating grate boiler-stokers	Losch Furnace Co., Schuylkill Haven, Pa. Anthrastube Axeman-Anderson Co., Williamsport, Pa.	From 1,125 to 6,300 sq ft steam (E.D.R.) Capacities to 260,000 Btu/hr. Year-round service water	1. Barley 2. Rice 1. Pea	Nonclinker or very soft clinker	Not sensitive to quality or coal sizing
Commercial and Small through Medium Industrial					
Stationary grates: Herringbone	Carbondale Grate Bar Co., Scranton, Pa.	Division of tonnage as between various types of commercial hand-firing impossible; but all types together probably account for some 400,000 tons of barley and the bulk of the 4,300,000 tons of rice annually.	1. Rice 2. No. 1 buckwheat would be rated 1 but for cost 3. Barley	Clinkering Uniform size Reasonable ash	Failure to clinker Excessive fines High ash (cost inconvenience)
Pyramid	Pyramid Grate Corp. Philadelphia, Pa. Various foundries	Also probably accounts for virtually all No. 1 buckwheat not in domestic use (7,763,000 tons in 1946)	Combustion rates, lb No. 1 buckwheat, 18-26 Rice, 18-23 Barley, 15-20	Soft to medium clinker to facilitate dumping. Size less important than stationary grate	Should not be so clinkering as to slag or stick to grates Ash has usual nuisance value but does not interfere
Pinhole				Nonclinking, uniform sizing	
Dumping grates: Slotted	Carbondale Grate Bar Co., Scranton, Pa.				
Herringbone	McClave Co. (McClave-Brooks Co.)				
Shaking grates	Combustion Engineering Co., and various others				
Semistokers (hand-operated)	McClave-Brooks Co., Scranton, Pa.	Sized from 100 to 600 hp. Largest approx 12- by 14-ft grate, 7 to 10 fpm setting required	1. Rice or No. 1 buckwheat (25 lb/sq ft/hr) 2. Barley (23 lb)	Nonclinker or very soft clinker. Special grate is available for screenings or culm	High ash materially increases the labor tending to cancel advantage of semistoker principle

Table 23-2. Principal Types of Equipment Available for Burning Anthracite.<sup>1</sup> (Continued)

Class of equipment	Typical manufacturers	Description of equipment, sizes and uses	Characteristics of coal		
			Optimum coal size (numbers refer to order of choice)	Desirable coal properties	Undesirable coal properties
Single-retort under-feed	Combustion Engineering Co., New York	"Skelly" stoker available 7 to 43.5 sq ft grate for 114 to 935 lb rice/hr	1. Rice. Barley not recommended	Non- or very lightly clinkering coal. High friability, reasonably low ash	Uniformity of sizing important because of tendency to clinker
Small traveling grate	Flynn & Emrich Co., Baltimore, Md.	7 to 45 sq ft grate area; 114 to 922 lb coal/hr			
	Hazleton Stoker Co., Hazleton, Pa.	Smallest practical size about 20 sq ft grate area	1. Barley 2. Rice	Uniform sizing desirable	Excessive clinkering
Industrial Fuel					
Chain-grate stokers	Illinois Stoker Co. Riley Stoker Co. McClave-Brooks Co.	Traveling grate differs from chain grate in that great segments may be removed without breaking continuity of chain  These stokers are among the most flexible, reliable means of burning anthracite in large installations	1. No. 4 buckwheat 2. No. 3 buckwheat (barley) 3. Rice, where the grates are in very bad condition only	Uniform sizing desirable but not always essential	Slag or clinker can be troublesome through sticking to grates, etc.
Traveling-grate stokers	(Coxe) Combustion Engineering Co. (Harrington) Riley Stoker Co.				
Pulverization	Various	Pulverization is a rapidly expanding method of burning the small sizes of anthracite	The smallest size of coal available, by reason of cost of fuel only	Sizing immaterial. Low friability desirable	Highly slagging coals are to be avoided unless furnace was designed for them
Miscellaneous Industrial Uses					
Gas producers	Wellman-Galusha, Cleveland and New York	Approximately 600,000 tons used annually on Galusha producers	1. Rice 2. No. 1 buckwheat (20% higher output but higher fuel cost)	Well sized, reasonably low ash (12%), min sulphur content, medium-volatile preferable	Should not clinker
Sintering ores	Dwight-Lloyd Sintering Co., Boston, Mass John E. Greenawalt, New York	257,000 tons used for agglomeration of fine ore in 1946-1947	1. culm, -20 +35 mesh gives optimum sinter results	Reasonable ash (12%) believed desirable, but conclusive data seemingly are lacking	High ash. The presence of large pieces of coal (wasted)
Cupolas	Various	Anthracite is still used as a cupola fuel to the extent of some 100,000 tons a year	1. Broken 2. Egg		

<sup>1</sup> Prepared with the cooperation of Anthracite Institute.

### LIGHTING BOILER FIRES—KINDLERS

**With Esso Fuel Igniter.** Until recently, the customary method of igniting a large boiler fire was to soak cordwood with kerosene, ignite, and cover with coal. Frequently as much as a cord of wood was required, and up to 2 hr elapsed until full operating pressure was raised. As an outgrowth of flame-thrower experience in the Second World War, Standard Oil Co. now offers the Esso fuel igniter, which is a blend of 10 per cent NaPalm aluminum soap thickener with 90 per cent base fuel similar to diesel distillate. A higher heating value is claimed, as is a greater safety factor.

**Procedure.** A bituminous-coal bed is built running across the front half of the furnace. The remaining grate area is covered with ash to prevent loss of draft. A transverse trench is dug through the center of the fuel bed. This trench is lined for its full length with heavy roofing paper. Esso fuel igniter is distributed evenly along the bottom of this paper trough; approximately 5 gal (35 to 45 lb) of igniter are sufficient for the average (30,000 lb steam per hr) boiler. The furnace may now be lighted or simply held in readiness for an indefinite length of time.

Immediately after touching off the igniter, the blowers are turned on slowly, and after approximately 3 min a full fire is bringing the boiler up to pressure; in 10 min stokers can be started, and full pressure should be reached in about 30 min. This short lighting period obviates the need for holding boilers in banked readiness in many cases.

**Lighting Anthracite with Esso Fuel Igniter.** While experiments to determine the best procedure for igniting anthracite-stoker fires were still in progress at the time of going to press, Esso reports:

The fuel igniter was spread in four strips, each about 6 in. wide and 18 in. apart, lying on a quadruple thickness of newspaper on top of the fuel bed with no recessed channel. After burning for 5 min, the blower was turned on gradually, and in 15 min more the anthracite was burning. \*

### HAND FIRING

#### Hand-firing Bituminous Coal<sup>1</sup>

**Starting the Fire.** After covering the grates with small sizes of coal to a depth of about 6 in., place wood kindling and paper on top of the coal at the rear of the grates and ignite. Do not use highly flammable gasoline or oils for igniting the coal.

In general, there are two accepted methods of hand-firing soft coal, the "spreading" and the "coking." The spreading method is used for high steaming rates; the coking method for high efficiency and a minimum of smoke and soot.

**Spreading Method.** In this method a small amount of coal is fired at a time and spread over only a part of the grate. If the fuel bed is burning down evenly, the coal may be spread evenly from front to rear on one section of the fire. If there are thin spots in the fuel bed, the coal may be spread over these spots. In this way the fuel bed is only partly covered with fresh coal at any one time. The thickness of the fuel bed that should be carried ordinarily may range from about 4 to 10 in., depending upon the draft, the load on the boiler, and the kind of coal.

**Coking Method.** With this method, a considerable amount of coal is fired at the front of the grates, forming a mound of fresh coal. When this coal is nearly or entirely coked and has given off most of its smoky gases, it is shoved back over the back part of the grates, leveling up the hot fuel bed. Fresh coal is then charged on the front portion of the grates by placement against the live coals previously pushed back, but not covering the same. The amount of live coals to be pushed back should about equal the amount of fresh coals to be added. Do not, however, allow the fire to burn too low before refueling. In this method, the combustible gases, mixing with overfire air,

<sup>1</sup> A Guide for Reducing Fuel Consumption in Commercial Plants, *U.S. Bur. Mines Bull.* 446, pp. 3-5, 1947.

will burn when ignited by the live coals, thereby providing a hot fire with a minimum of smoke and soot. Overfire air should be provided through the fire door. The fuel bed should be carried as deep as the draft will permit.

The **alternate method**, in reality a variation of the coking method, is sometimes used. First push all live coals to one side of the grate, then place fresh coal on the side opposite the live coals and touching the same. Continue to place the fresh coal on alternate sides each time coal is added.

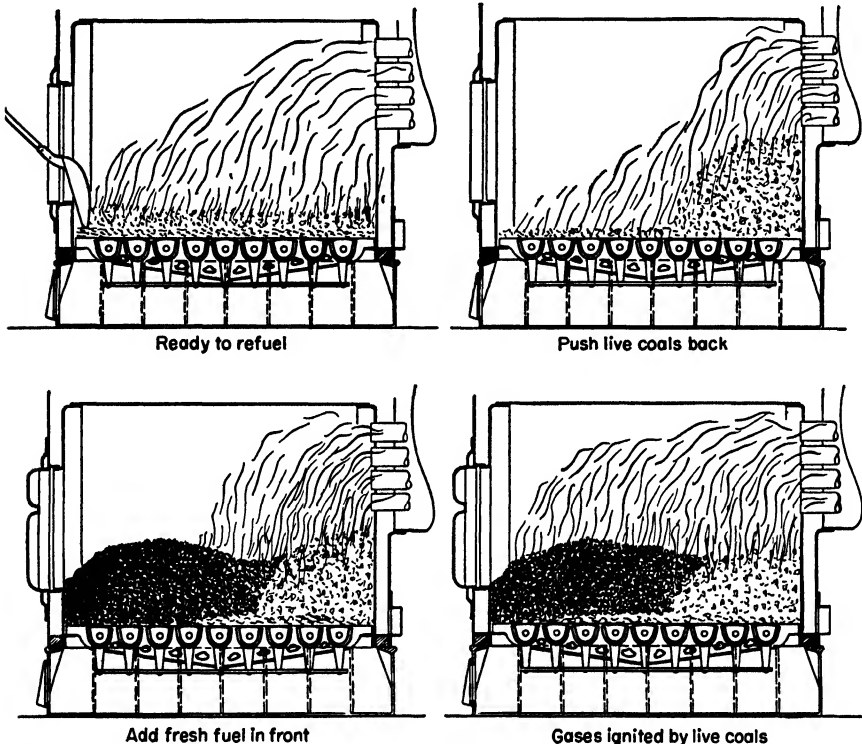


FIG. 23-1. The coking method of firing bituminous coal. (Kewanee Boiler Company, Kewanee, Ill.)

### General Rules for Hand Firing

The efficiency obtained with hand firing depends largely upon the fireman. According to the U.S. Bureau of Mines, a good fireman may use some 20 per cent less coal than a poor fireman. To learn the best method of firing a particular boiler may require considerable study and trial, but the following general rules will prevail in all cases:

1. Only enough air should be used to prevent smoke and too much unburned material going out the stack. Control the amount of air flowing through the grates by means of the uptake damper, not the ashpit doors, whenever possible.
2. The excessive use of firing tools and grate-shaker bar should be avoided to prevent an excess of undesirable unburned fuel in the ashes.
3. Study the flaming of the fire and its color. Watch for dark smokiness. Where there is too much flaming or smoke, it is generally necessary to let some air into the furnace over the fuel bed, such as through the slots in the fire doors.

4. Good firing includes noting fuel-bed conditions as to thickness, holes, caking, and clinkering. To avoid clinkers, keep the ash as cool as possible. Do not "bar" the fire so as to throw ash up into the hot fuel.

5. Sometimes, dampening bituminous coal slightly with water improves fuel-bed conditions.

**Table 23-3. Specifications for Hand-fired Grates<sup>1</sup>**

Kind of coal	Pressure	Type of plant	Type of grate	Size of coal	Mesh grate, in.	Approx per cent free air space	Kind of draft
Bituminous coal	High	Industrial	Shaking	Run-of-mine Slack	$\frac{3}{8}$ $\frac{1}{4}$	43 35	These grate meshes will work satisfactorily under natural draft. Forced draft may be used without change of grates wherever overrating of boiler is desired
	High	Heating	Shaking	Run-of-mine Slack	$\frac{3}{8}$ $\frac{1}{4}$	43 35	
	Low	Heating	Shaking	Run-of-mine <sup>a</sup> Slack <sup>a</sup>	$\frac{3}{8}$ $\frac{1}{4}$	43 35	
	Low	Heating	Shaking and dumping	Run-of-mine <sup>b</sup> Slack <sup>b</sup>	$\frac{3}{8}$ $\frac{1}{4}$	44 38	
Anthracite	High	Industrial and heating	Dumping	No. 1 buckwheat No. 2 buckwheat (rice) No. 2 buckwheat (rice) No. 3 buckwheat (barley) Culm	$\frac{1}{4}$ $\frac{1}{8}$ $\frac{1}{4}$ $\frac{3}{4}$ $\frac{3}{4}$	32 19 32 12 7	Natural Forced Strong natural Forced
	High and low	Heating	Shaking and dumping	Pea No. 1 buckwheat No. 2 buckwheat (rice) No. 2 buckwheat (rice)	$\frac{3}{8}$ $\frac{1}{4}$ $\frac{3}{4}$ $\frac{1}{4}$	44 38 29 38	Natural Natural Forced Strong natural

<sup>1</sup> "Finding and Stopping Waste in Modern Boiler Rooms," 3d ed., p. 143, Cochrane Corp., Philadelphia, 1928.

<sup>a</sup> Large brick-set boilers.

<sup>b</sup> Firebox-type boilers.

**Table 23-4. Ratio of Heating Surface to Grate Surface for Various Fuels**

	<i>Sq Ft</i>
No. 1 buckwheat anthracite.....	1:40
No. 2 buckwheat anthracite (rice) ..	1:35
No. 3 buckwheat anthracite (barley) ..	1:30
No. 4 buckwheat anthracite. ....	1:25
High-grade bituminous coal .....	1:55
Medium-grade bituminous coal... ..	1:50
Low-grade bituminous coal .....	1:45

**Table 23-5. Ratio of Heating Surface to Grate Surface for Various Bituminous Coals<sup>1</sup>**

Coal	Grate-bar openings		Ratio for economy		Ratio for capacity	
	Mine run	Slack	Mine run	Slack	Mine run	Slack
Va., W. Va., Md., Pa .....	$\frac{1}{2}$	$\frac{3}{8}$	1:60	1:55	1:55	1:50
Ohio, Ky., Tenn., Ala .. .	$\frac{3}{4}$ - $\frac{1}{2}$	$\frac{1}{4}$	1:55	1:50	1:50	1:45
Ill., Ind., Kans., Okla .. .	$\frac{3}{4}$ - $\frac{1}{2}$	$\frac{1}{4}$	1:50	1:45	1:45	1:40
Colo., Wyo ..	$\frac{3}{8}$	$\frac{1}{4}$	1:50	1:45	1:45	1:40

<sup>1</sup> MARKS, LIONEL S., "Mechanical Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1941.



### General Care of Equipment

1. All undesirable leaks through brickwork, around headers, doors, peepholes, shells, drums, soot blowers, or into the breeching and chimney should be effectively sealed (such leaks may be detected with a candle).
2. All gas passes should be kept clean; the water side of the boiler should be kept clean; and all furnace brickwork and baffles should be maintained in good condition.
3. All hot surfaces should be insulated.
4. All controls, instruments, and dampers should be kept in good working order.

### Methods of Hand-firing Commercial Sizes of Anthracite<sup>1</sup>

The primary rule in firing any size of anthracite is "let it alone." This applies to barley and such other small sizes as may be fired industrially or commercially as well as to the larger sizes.

The U.S. Bureau of Mines recommends burning coal rapidly and at high temperatures in order to secure the best economy. Fire small quantities of coal at short intervals so that thin places will not burn through and admit large quantities of excess air. The quantity of coal fired on each occasion depends upon such factors as grate area, load, and draft. Firing and cleaning should be so coordinated as to produce a total fuel-bed depth of not over 6 to 8 in. *just before cleaning*. This should be considered the full-load fuel-bed depth; in periods of light loads, the attention required may be considerably decreased by firing materially more heavily.

In the case of all barley equipment, the drafts should be adjusted so that the surface of the fuel bed just begins to "float" without either being dormant or "boiling" too violently.

**Spreading Method of Firing.** In the spreading method, sometimes called the "alternate" method, a small amount of coal is fired at one time and spread evenly over the fuel bed from the front to the rear. The firing is done in alternate fire doors so that the entire fuel bed is not blanketed with green coal at the same time. Hand-firing practice leans more and more to the spreading method.

**Cleaning Hand Fires.** Cleaning the fire is necessitated by the fact that clinker and coarse ash will not pass through the grates. The interval between cleanings depends upon the amount of coarse ash in the coal, the character of the ash, and the type of grate. If the coal contains much ash, or ash that is fusible, the fires may have to be cleaned often; if light fires are being carried, less clinker or ash forms, and the fire can often be run through a shift without cleaning.

While the frequency of cleaning is thus necessarily a function of the design, boiler load, quality of fuel, etc., it is highly desirable to design and operate so that they will not have to be cleaned oftener than once per 8-hr shift, as this is easier on both labor and equipment. As cleaning intervals are, in the final analysis, determined by the amount of ash accumulated, Fig. 23-2 shows the depth of pure ash produced in each hour under various conditions.

The **cleaning of a banked fire** should be done about 2 hr before steam is needed. It is advisable to bank the fire at the front of the grate near one of the doors. This exposes the clinkers, which can then be removed more readily.

It is good practice to clean only one-half of a boiler at a time, skipping every other door, and going back to them only after the row has been completed. This method assures a more continuous output, higher  $\text{CO}_2$ , and a more complete combustion of the gases.

When cleaning is started, there should be sufficient burning coal in the furnace so that enough will be left to start a hot fire quickly when the cleaning has been com-

<sup>1</sup> JOHNSON, ALLEN J., The Combustion of Barley Anthracite, *Trans. ASME*, July, 1944, pp. 399-406.

pleted. If a light fire is being carried, it may be necessary to put some fresh coal on the side to be cleaned last. During cleaning, the damper should be partly closed.

Cleaning should always be done thoroughly. All clinker and ash should be removed, with particular attention to any that might adhere to the side walls. Refuse should be removed in such a way as to waste a minimum amount of combustible.

There are two principal methods of cleaning hand-fired furnaces:

In the **side method**, one side of the fire is cleaned at a time. The good coal and fire is first pushed from one side to the other. The clinkers then may have to be removed from the grates by means of a slice bar. When they have been loosened and broken up they are dumped into the ashpit or, on a stationary grate, pulled out of the furnace with a hoe. In the latter case the fireman should gather the clinker on the front part of the grate before pulling it out into a wheelbarrow, as this lessens his exposure to the heat. After the one side has been cleaned, it is next advisable to spread a thin layer

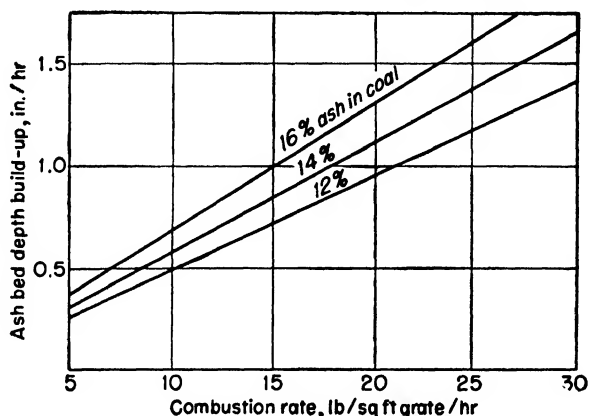


FIG. 23-2. Amount of ash that will accumulate between cleanings. (Johnson, Allen J., *The Combustion of Barley Anthracite*, Trans. ASME, 1944.)

of coal on the grates so that the full heat of the live fire will not rest directly on the grates. The burning coal from the other side may then be moved over to the clean side. At this point, a few shovelfuls of fresh coal are added in order to have enough burning coal to cover the entire grate when the cleaning is completed. (This addition of coal is important, especially when the cleaning must be done with a load on the boiler.) The clinkers are then removed from the second half of the grate and the fire respread over the entire grate to complete the cleaning. In cases where the load is heavy, a time interval may be necessary between cleaning the two halves of the grate, in order to allow the new fire to build up to its load-carrying capacity.

A fireman, after becoming familiar with the side-cleaning method, should be able to clean a 200-hp boiler furnace in 10 to 12 min.

In the **front-to-rear method** of cleaning, the burning coal is pushed with a hoe against the bridge wall. It is usually preferable to clean one-half of a grate at a time. The clinker is loosened and pulled out of the furnace, and the burning coal is then respread evenly over the grate. If the front-to-rear method must be used while the load is on the boiler, the side method should be employed after the day's run is over, so as to prevent a large accumulation of thick hard clinker at the bridge wall.

Some firemen have a habit of pulling the clinkers out of the furnace without scraping and pushing the burning coal against the bridge wall or to one side. They merely run a slice bar under the clinker to lift it to the surface of the coal, and then remove

the large pieces with a hoe. Small pieces are not easily detected and are thus left in the fire. These fuse in a few minutes, because of the high temperature near the surface of the fuel bed and the air deficiency under the clinker. Thus more masses of clinker are formed which are usually worse than those removed. This habit should be discouraged, as it is not really a method of cleaning a fire.

**Thickness of Fuel Bed.** The ideal thickness will depend on the size of anthracite burned. The smaller the size the thinner the fuel bed should be for maximum fuel

**Table 23-6. Air Required for Burning Anthracite<sup>1</sup>**

CO <sub>2</sub> in furnace, per cent	Excess air, per cent	Total air required (at 90°F)/lb coal	
		Lb	Cu ft
6	225	32 0	445
8	150	24 6	342
10	100	19 7	274
12	65	16 2	226
14	43	14 1	196
16	25	12 3	172

<sup>1</sup> JOHNSON, ALLEN J., *The Combustion of Barley Anthracite*, *Trans. ASME*, July, 1944, pp. 399-406.

a V-shaped angle. A choice between the pinhole and slotted types is largely a matter of manufacturer and consumer preference.

While both **dumping** and **stationary** grates are available, a substantial percentage of all grates now being sold is of the dumping type. Grates that dump to the center have the advantage of keeping hot ash away from the front of the ashpit and the rear ash closer to the point of removal. Dumping grates will usually weigh between 60 and 80 psf.

The minimum practical **limitation of size** for all such grates is about 10 sq ft; the maximum, a fuel-bed length of about 10 to 12 ft, as limited by the distance that the fireman can effectively throw the coal and handle the fire.

Important **points of design** are the percentage of free air space and the uniformity of air delivery. If the free air space through the grates is less than 4 per cent, they are likely to restrict unduly the flow of air through the grates and thus necessitate excessive velocities; on the other hand, if the free air space exceeds 8 to 10 per cent of the grate area, the velocity will be so low for the required volume of air delivery that much of the desired "jets" or blast effect will be lost. Uniformity of air delivery is unusually important because the air delivery of the individual air openings is so localized that either dead or unusually active areas on the grates of only a few square inches will result in ridges or patches of less or more active combustion with corresponding somewhat spotty fires.

Nevertheless, as Bato<sup>2</sup> points out, the question of the proper design of grates has been somewhat overemphasized, since there are really only two major points involved: (1) excessive sifting of the coal into the ashpit, and (2) the danger of holes being blown into the fuel bed in the case of too large air openings. As to item 1, it must be remembered that, except immediately after cleaning the fire, the coal does not rest on the grate but on the ashes of the coal burned previously. Accordingly, if grates with

economy and output. With buckwheat No. 1, the total fuel-bed thickness should be about 6 in.; for buckwheat No. 2 (rice), 4 to 5 in. Never cover the fuel bed completely with fresh coal. Fire frequently and, in effect, sprinkle coal on the surface of the fire. Keep the fires free from blowholes, and maintain level fires for uniform burning.

#### **Hand-fired Grates for Commercial Sizes of Anthracite<sup>1</sup>**

Hand-fired grates for the barley (and smaller) sizes of anthracite should be of the **pinhole** or **slotted** type. The latter are commonly known as **herringbone** grates when the adjacent rows are set at

<sup>1</sup> JOHNSON, ALLEN J., *op. cit.*

<sup>2</sup> BATO, A. A., consulting engineer, East Orange, N J., in a written discussion of the paper by Johnson.

small openings are not available, the fireman may either cover the **grates** after cleaning with a thin layer of ashes or, preferably, small-sized clinkers, or use a small quantity of larger sized coal for this purpose. As for item 2, the danger of holes being blown into the fuel bed is somewhat more serious, but prevails only for the first half hour or so after fire cleaning and can be minimized by a little care and checking. To these points must be added the retardation of combustion due to restricted air openings or inadequate underfire blast pressure.

The **size of pinholes** ranges from  $\frac{3}{16}$  to  $\frac{5}{64}$  in., depending upon the manufacturer. They should be flared or tapered underneath to make them self-cleaning and to secure a modified venturi effect. The distance between individual pinholes is usually about  $\frac{3}{4}$  in.; and the over-all metal thickness of the grates is usually about the same.

While individual manufacturers and patentees sometimes emphasize the specific design of their holes and slots, Bato<sup>1</sup> calls attention to the fact that the direction,

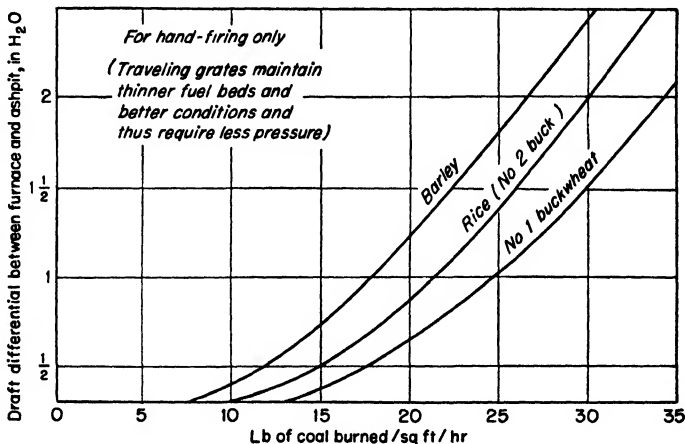


FIG. 23-3. Draft required at different combustion rates for the commercial sizes of anthracite. (Johnson, Allen J., *The Combustion of Barley Anthracite*, Trans. ASME, 1944.)

shape, etc., of the actual air jets reaching the live coal are determined by the ashes immediately under the burning coal at all stages excepting immediately after cleaning.

The **maximum combustion rate** recommended for barley anthracite on shaking or dumping grates is 15 to 20 psf of grate per hr.

With both hand-firing and semistokers, it is necessary to provide sufficient **maximum air pressure in the ashpit** to burn the coal properly when the fuel bed is at maximum thickness, *i.e.*, just before cleaning. A static pressure of  $2\frac{1}{2}$  in. water gauge is usually suitable for fans when delivering the rated quantity of air for barley anthracite (see Fig. 23-3). (This refers to the maximum pressure that should be available to the operator rather than to the operating pressure, as the latter will be solely dependent upon such factors as fuel-bed thickness and rating.)

As on other types of combustion, balanced draft conditions are to be preferred to minimize furnace infiltration.

#### Semistokers (or Hand Stokers) for Anthracite

The semistoker, or hand stoker, manufactured as "*MA*" grates by the McClave Co., Allentown, Pa., are especially suited to the burning of barley or rice anthracite in commercial and industrial installations. These units consist of a suitably inclined

<sup>1</sup> *Op. cit.*

dumping grate, usually of the slotted type, having openings approximately  $\frac{3}{4}$  in. wide and a total air space of approximately 8 per cent. The grates are combined with overhead coal hoppers equipped with gates which, upon manual operation, drop coal to a horizontal ledge in front of the grate, from which it can be readily pushed onto the sloping fuel bed. The system is thus an improved method of hand-firing anthracite, with an elimination of manual handling of the coal to the boiler, rather than a stoker. Forced draft is used in conjunction with "MA" systems; its strength, together with the boiler ratings which must be produced, largely determines whether barley can be, or rice must be, used.

**Sizes Available.** Semistokers are available in a full range of sizes up to about 12 ft long and 14 ft wide, with capacities from 100 to 600 developed hp. Approximately 7 to 10 ft of setting height is recommended for their installation. Coal-burning

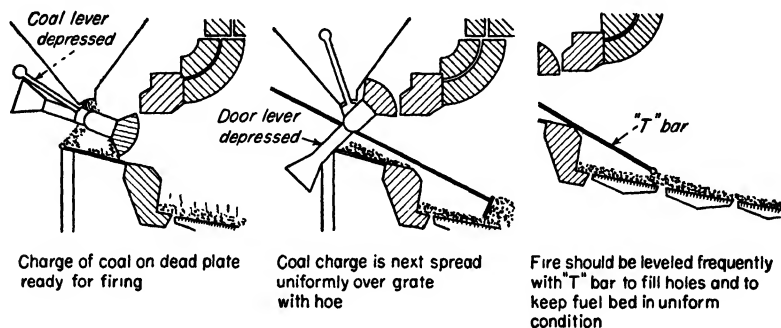


FIG. 23-4. Proper method of operating a McClave hand-stoker.

capacities range from 18 to about 23 lb on barley to about 25 lb maximum on rice. Material reductions in capacity may be experienced if the coal is poorly sized, such as with large amounts of dust or fine material, or high in ash, such as above about 15 per cent.

**Operating Characteristics.** Manual attention is reduced to spreading the coal by hoe, leveling the fire at intervals, cleaning the fire, and dumping the ash or clinker. Labor is thus less than for conventional hand-firing, through the elimination of coal handling outside of the boiler and hand shoveling to the furnace. Somewhat more uniform, better conditioned fuel beds can be carried, with resultant slightly higher boiler loads than on conventional dumping grates (Fig. 23-4).

### SINGLE-RETORT UNDERFEED STOKERS<sup>1</sup>

Considered numerically, the single-retort underfeed stoker is one of the most important coal-burning appliances in use. The stoker as a type has been in operation for approximately half a century, with many thousands in use. It is most popular for heating plants, process steam in moderate amounts, power generation for industrial plants, and small utilities. In fact, a consideration of first cost and efficiency of an installation which will comply with strict smoke ordinances makes the single-retort underfeed stoker a serious competitor to all equipment in the small and medium power and heating fields.

While the single-retort side-dump type of stoker is always classed as of the underfeed principle, it actually combines both overfeed and underfeed burning in that, whereas the retort area in which the volatile gases are burned is a true underfeed zone, the side grates on which most of the fixed carbon is burned are really an overfeed area.

<sup>1</sup> "Combustion Engineering," Combustion Engineering-Superheater, Inc., pp. 3.1*f.*, 1947. Single Retort Underfeed Stoker Firing, Fairmont Coal Bureau, *Reference Bul.* 9.

**Principles of Operation.** Coal is fed into the base of a narrow horizontal trough-shaped retort by means of either a plunger (Brownell, C-E Low-Ram, Detroit, Riley, Westinghouse, etc.), a reciprocating retort bottom (C-E type E), or a worm (Iron-Fireman, Winkler). The C-E Skelly uses a combination of the worm and plunger in that a worm conveys coal from the hopper to the retort entrance and a reciprocating feeder unit distributes it in the retort itself.

In general, the larger stokers use some type of plunger or reciprocating feed, with worm feeds being restricted to smaller models.

**Stationary and Moving Grates.** The coal fed from the hopper travels away from each side of the retort (or one side in the side-retort models) over the grates toward the side walls. In the case of stationary-grate stokers (Riley and most other makes), the side-wall movement of the coal and ash is effected partly by gravity acting along the downward incline of the grate surfaces, and partly by the pressure exerted by the

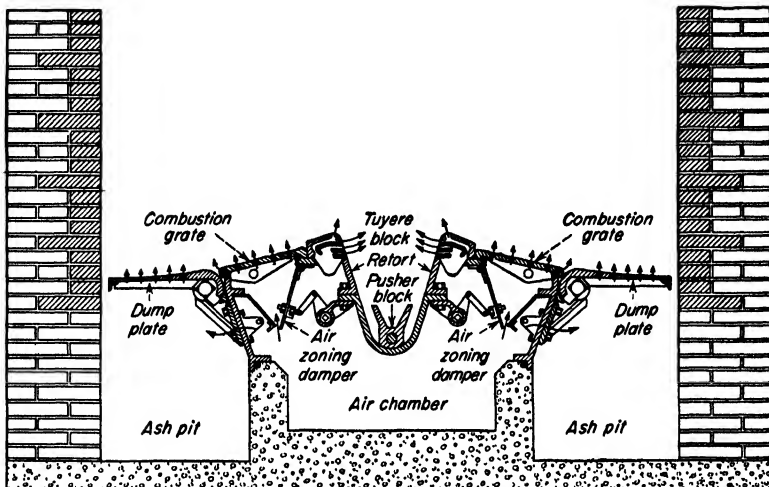


FIG. 23-5. Cross-section of single-retort, side-dump, underfeed stoker stationary grates. (Riley Stoker Corp.)

incoming fresh coal. In stokers having mechanically agitated grate bars (C-E type E, C-E Skelly), sideward travel of the fuel is effected by the motion of the grate, aided somewhat by gravity and the pressure of the incoming coal.

Air is supplied under pressure to the grates, which extend a short distance downward into the retort to provide for admitting air to the coal while still in the retort.

In extremely narrow stokers, active combustion occurs directly over the retort as the coal moves upward to the fire. In wider stokers, the coal usually ignites as it passes the boundaries of the retort, so that active combustion occurs only over the grate proper.

While such auxiliary means as the quick thrust of the plunger of the Riley stoker are designed to increase the porosity of the fuel bed on the stationary-grate models, as well as to improve the characteristic flow of the fuel across the grate, the maximum width of stationary-grate underfeed stokers is about  $6\frac{1}{2}$  to 7 ft for the most satisfactory operation. While widths greater than these are frequently encountered, there is usually a tendency toward uneven fuel beds, lack of uniform air distribution, and a necessity for considerable manual leveling of the fire. Moving reciprocating grates which distribute the fuel mechanically are commonly installed to furnace widths of about 12 ft.

**General Principles of Combustion.** The fuel bed is usually heavier over the center of the retort than at any other part of the fuel-bed area, this being particularly pronounced in stationary-grate stokers. The volatile gases are driven off and burned over this portion of the fuel bed. Consequently more air is required at this stage of combustion to burn these gases properly, and it is thus customary to design the tuyère openings so as to allow relatively free air passage at this point. As the fuel passes out of the retort proper and over the tuyère blocks, a second stage of combustion is encountered, that of the caking of the coal. As smaller quantities of air are required for proper combustion at this stage than for the burning of the volatile gas, air to this section should be restricted, by either basic design or dampers. Any unburned fuel remaining after passing over the combustion grates is burned on the dump plates. Here again, the pressure of the air should be controlled in accordance with the amount of fuel being so burned. After the fuel is completely burned, the dump plates are periodically lowered and the ash discharged into the pit for removal.

The furnaces in single-retort underfeed stokers usually comprise simple vertical refractory walls and, as no ignition or combustion arches are required, much of the heat of the fuel bed is transferred to the boiler surfaces by radiation.

**Center- and Side-retort Types.** In addition to being available with either stationary or reciprocating grates, two further generic subdivisions of single-retort stokers are in use, those with the retort in the center and having two dump plates, and those with the retort at one side of the furnace and only one dump plate. An advantage of the latter type, particularly in the smaller furnaces, is that a larger proportion of the available furnace width may be devoted to active grate-bar area.

Earlier models were frequently built with dead plates at the sides, instead of dump plates. Ash was removed by hoeing the clinker to the front of the boiler. Because of the very decided superiority of the dump-plate type, these are considered obsolete.

**Sizes and Capacities Available.** Single-retort underfeed stokers are manufactured in several distinctive designs, by a number of builders, and in sizes ranging from less than 10 sq ft of grate area to more than 125 sq ft. Corresponding coal capacities are 100 to 6,800 lb per hr. The upper limits in both cases are for reciprocating-grate models.

The greater furnace widths which can be handled by the moving-grate types give them a higher maximum output than the stationary-grate designs. According to "Combustion Engineering," reciprocating-grate models are applicable for installations under boilers having up to 7,000 sq ft of heating surface and developing peak capacities to 60,000 lb steam per hr. The permissible continuous combustion rate corresponding to this peak would be 40,000 to 45,000 lb steam per hr.

Stationary-grate models are usually considered to be suitable for burning coals at continuous capacities up to 25,000 lb steam per hr and to be capable of handling peaks to about 45,000 lb steam per hr. They should rarely be considered for regular heavy duty at loads in excess of 30,000 lb per hr.

**Adaptability to Varying Loads.** The single-retort stoker is well adapted to a widely varying load and, when properly applied and equipped with adequate instruments and controls, is capable of highly efficient combustion performance over a load range of about 4 to 1.

This type of stoker is also characterized by its ease and simplicity of operation and adjustment. This capacity range includes more than 75 per cent of the number of commercial and industrial boilers installed in this country.

**Permissible Combustion Rate and Heat Release.** The permissible combustion rate is a function of the stoker width because, as the over-all width of the machine is increased, the dumping-grate area becomes a decreasing percentage of the total stoker grate area. For very small stokers, such as the smaller models of the *Skelly* (Combustion

tion Engineering-Superheater, Inc.), the combustion rates are preferably limited to 18 to 20 psf of grate per hr continuously, with 2-hr peak ratings of about 25 lb. For stokers having a width of some 6 to 7 ft, the permissible continuous combustion rate, with a suitable coal, is about 30 lb/sq ft/hr, with 2-hr peak ratings of 40 to 45 lb. On the wider stokers, 10 ft and over, continuous combustion rates of 40 lb/sq ft/hr are practical, with 2-hr peak ratings up to 55 lb.

With furnaces having refractory walls, and in which the fuel bed is exposed to the boiler surfaces, the preferred continuous maximum rate of heat release is around 45,000 to 55,000 Btu per cu ft of furnace volume per hr, and around 75,000 Btu for 2-hr peaks. These rates of heat release may be increased somewhat under the most favorable conditions, as, for example, if water-cooled surfaces are used on one or more of the furnace walls, or if the grate area is liberally proportioned so that the combustion rates are relatively low. For example, in water-cooled furnaces, such as firebox

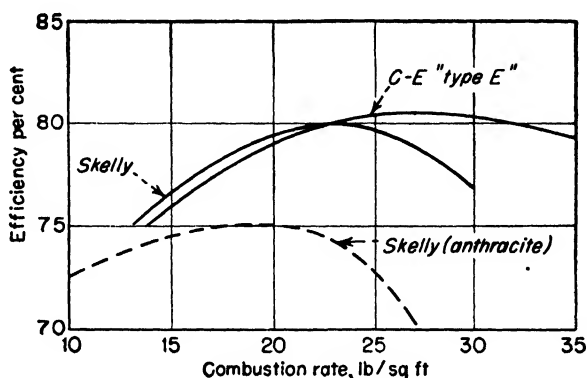


FIG. 23-6. Efficiencies of single-retort underfeed stokers. NOTE: These curves are based on a constant exit-gas temperature of 500°F. To arrive at a true comparative efficiency, a correction factor of approximately 3 per cent per 100°F difference between 500° and the actual boiler outlet temperature must be applied. (De Lorenzi, Otto, "Combustion Engineering," Combustion Engineering-Superheater, Inc., New York, 1947.)

steel boilers and cast-iron heating boilers, the permissible rates of heat release may be as high as 100,000 to 120,000 Btu/cu ft/hr continuously, with 2-hr peaks up to 150,000 Btu.

On the other hand, if the stokers are set in Dutch-oven furnaces in which the fuel bed is not exposed to the boiler surfaces, the permissible rates of heat release must be reduced to avoid excessive refractory maintenance.

**Air Pressure Required.** The air pressure required in the main air chamber, for various rates of combustion, varies somewhat according to the design of the stoker. In general, a stationary grate, having a relatively deeper fuel bed at the center of the retort, will require a higher pressure for a given coal consumption than will a grate having moving bars. As examples, "Combustion Engineering" cites requirements of 1.0 in. water gauge for each 10 lb coal per sq ft of grate per hr for their moving grate *type E* and *Skelly* (bituminous) stokers, 1.25 in. water gauge for each 10 lb coal per hr for their *C-E Low-Ram* stationary-grate stoker, and 1.0 to 1.25 in. water gauge (total) for their *anthracite Skelly* operating at permissible combustion rates of 22 to 25 psf on rice anthracite.

**Coals Suitable for Single-retort Underfeed Stokers.** Single-retort underfeed stokers are designed to burn caking, or moderately caking, bituminous coals and certain free-burning bituminous coals and, to a lesser extent, other grades of coal or waste fuels, such as wood refuse, in combination with such coal. In practical appli-



Table 23-7. Test Results with Single-retort Underfeed Stokers with Various Coals<sup>1</sup>

Stoker	Combustion Engineering type E stoker, moving grate									
	32 26 Georges Creek	Cumber- land	53 4 Pennsyl- vania bi- tuminous	59 0 Berwind White	57 5 Southern Star H & S	64 4 Jenner bitumi- nous	47 9 Cherokee Kans.	46 2 Colorado lignite	46 Illinois	50 Alabama
Ratio heating surface to grate surface										
Kind of fuel										
Heat value/lb (dry), Btu	14,040	14,404	13,614	14,936	13,818	13,920	12,746	11,648	12,495	14,376
Actual evaporation/sq ft/hr, lb	4 40	8 10	4 65	3 61	2 95	6 72	4 61	4 61	3 40	4 21
Dry coal/sq ft/hr, lb	23 9	20 2	34 8	21 4	28 0	54 4	23 9	19 1	17 8	20 2
Boiler exit-gas temp, deg	535	659	598	540	546	513	504	502	463	584
Efficiency, per cent	79 2	71 4	75 4	77 6	75 8	67 2	75 8	70 9	74 7	73 0
Combustion Engineering Skelly, moving grate										
C-E Low-Ram stoker, stationary grate										
Ratio heating surface to grate surface										
Kind of fuel										
Heat value/lb (dry), Btu	13,703	13,680	13,930	13,560	12,200	12,550	12,725	14 250	12,800	14,533
Actual evaporation/sq ft/hr, lb	3 50	6 52	4 13	6 60	4 91	3 32	4 01	4 35	4 42	4 57
Dry coal/sq ft/hr, lb	14 7	25 8	16 8	26 5	17	20 5	20 2	18 2	19 1	13 0
Boiler exit-gas temp, deg	432	580	520	510	542	563	548	538	511	506
Efficiency, per cent	79 5	77 3	75 9	79 3	73 8	72 5	71 9	78 4	73 9	77 1

<sup>1</sup> Combustion Engineering-Superheater, Inc.

cation, fuels ranging from lignite to anthracite are being burned successfully. However, this type of stoker is most widely used for burning Eastern caking and mildly caking bituminous coals, and those Middle Western free-burning bituminous coals which have an ash-fusion temperature sufficiently high for successful utilization in the relatively thick fuel beds that characterize underfeed firing.

For satisfactory stoker operation, coal sizing is as important as coal analysis. The size of coal best suited to single-retort underfeed stokers may be specified as follows:

The fuel shall be bituminous coal with a size consist of approximately equal proportions of nut, pea, and slack, these three sizes of coal being defined as follows:

1. Nut coal of a size passing through a  $1\frac{1}{4}$ -in. round-hole screen and retained on a  $\frac{3}{4}$ -in. round-hole screen
2. Pea coal of a size passing through a  $\frac{3}{4}$ -in. round-hole screen and retained on a  $\frac{5}{16}$ -in. round-hole screen
3. Slack coal of a size that will pass through a  $\frac{5}{16}$ -in. round-hole screen

In the event that difficulty is experienced in obtaining commercial coal sized to these close limits, the following alternate sizing is usually acceptable:

Bituminous coal of a size known commercially as 1- to  $1\frac{1}{2}$ -in. nut and slack, and shall preferably contain not more than 50 per cent slack, slack being defined as coal of a size that will pass through a  $\frac{1}{4}$ -in. round-hole screen.

It is usually recommended that individual lumps of coal be not larger than  $1\frac{1}{4}$  in., particularly when the fuel is of a hard mechanical structure. However, many of the Eastern bituminous coals are friable, and sizes known commercially as 2-in. "resultant" or even  $2\frac{1}{2}$ -in. "resultant" may be satisfactorily used because, with these friable coals, the degradation in transit and handling is sufficient to reduce the lumps to sizes that burn well in this type of stoker.

**Anthracite on Underfeed Stokers.** Number 2 buckwheat, or rice, anthracite is being used successfully on underfeed stokers that have been especially designed for its use at coal-burning rates of from 100 to 500 lb per hr (total).<sup>1</sup> Specific design for anthracite is most important, since attempts to substitute anthracite for bituminous on many stokers results in materially lowered combustion rates and such difficulties as avalanching of the coal and/or clinkering. In sizes such as these, moving grates are highly advantageous. *Skelly and Flynn & Emrich* are outstanding examples of stokers using anthracite.

### Factors in the Selection of Bituminous Coals for Residential Stokers<sup>2</sup>

The great majority of bituminous-coal stokers used in residential installations are of the clinkering type. Because of inherent characteristics of the underfeed combustion process as it occurs in these small stokers, and because of the wide range of operating conditions encountered, not all bituminous coals can be used successfully in residential underfeed units. Further, at the present time, a standard test procedure for the evaluation of coals for use in residential stokers is not available. In fact the only criteria of any real value to date are actual performance tests on stokers of typical operating characteristics.

Battelle Memorial Institute, Columbus, Ohio,<sup>3</sup> recently reported upon a series of such tests on 33 bituminous coals. Of these they list several as suitable for residential stoker use, as is shown in Table 23-8. As several committees and research groups are making similar studies, it is likely that this list will be greatly expanded.

**Reasons for Unsatisfactory Performance.** In view of the difficulty of presenting the coal requisites, the following negative approach is necessary; *i.e.*, unsatisfactory

<sup>1</sup> In addition there are several makes of round-retort domestic-type anthracite stokers with buckwheat and rice capacities of 15 to 85 lb per hr.

<sup>2</sup> PURDY, JAMES B., and HARLAN W. NELSON, *Mining Trans. AIME*, vol. 184, pp. 214-223, 1949.

coals were found to have one or more of the following general undesirable characteristics in the Battelle tests.<sup>1</sup>

1. Slow ignition with less than 20 lb coal burned during the first hour
2. Over 8 per cent ash content
3. Over 2600°F ash-softening temperature
4. Less than 20 per cent of the ash released converted to clinker
5. A smoke reading of over 12 units average during the off period
6. A wind-box pressure exceeding 1.25 in. water gauge.
7. Weight of coke at end of test exceeding 10 lb
8. Free-swelling index exceeding 8.0
9. It is assumed that the top size does not exceed 1¼ in. and that the amount of ¼-in. coal does not exceed that of normal resultant coals.

**Table 23-8. An Evaluation of Coals for Residential Bituminous-coal Stokers<sup>1</sup>**

Test	Bed	State	Class <sup>a</sup>	Reasons for classification	Actual marketing experience
1	Wallins	Ky.	S	.. . . .	No information
2	Wallins	Ky.	S	.. . . .	No information
3	Upper Freeport	Pa.	U	Strong coke-tree formation	No residential
4	Pittsburgh	W. Va.	S	.. . . .	No information
5	No. 2 gas	W. Va.	S	.. . . .	Successful
6	Taggart	Va.	S	.. . . .	Successful
7	Taggart	Va.	S	.. . . .	Successful
8	Chilton	W. Va.	U	Poor clinker and hold-fire	Not marketed
9	Sewell	W. Va.	S	.. . . .	No information
10	Pittsburgh	W. Va.	S-	Sluggish ignition, low clinker, above avg hold-fire	No information
11	Elkhorn	Ky.	S	.. . . .	Successful
12	Elkhorn	Ky.	S-	Poor clinker	No information
13	Elkhorn	Ky.	S	.. . . .	No information
14	Elkhorn	Ky.	S	.. . . .	No information
15	Elkhorn	Ky.	S	.. . . .	No information
16	Mason	Ky.	S	.. . . .	Successful
17	Mason	Ky.	S-	Poor clinker	Not marketed
18	No. 11	Ky.	S	.. . . .	Successful
19	High Splint	Ky.	S-	Clinker questionable	Successful
20	Blue Gem	Ky.	S	.. . . .	Mine closed
21	No. 2 gas	W. Va.	S-	Sluggish ignition, strong coke, low clinker	No information
22	(Unknown)	Ind.	S	.. . . .	Not marketed
23	Hazard No. 4	Ky.	S	.. . . .	Successful
24	Hazard No. 4	Ky.	S-	Inadequate clinker	Not marketed
25	Elkhorn No. 4	Ky.	S-	Inadequate clinker	Not prepared
26	Hernshaw	Ky.	S-	Poor clinker	Not marketed
27	Rich Mountain	Tenn.	U	Sluggish ignition and hold-fire, high coke, low clinker	Not marketed
28	Shannon	Va.	U	Sluggish ignition and hold-fire, high ash content	Not marketed
29	No. 2	Ky.	U	Poor ignition and hold-fire sluggish fire, high ash	Not marketed
30	No. 7	Ky.	S	.. . . .	Not marketed
31	Powellton	W. Va.	S	.. . . .	Not marketed
32	Hazard No. 4	Ky.	S	.. . . .	To be marketed
33	Clintwood	Ky.	S	.. . . .	Not marketed

<sup>1</sup> PURDY, JAMES B., and HARLAN W. NELSON, *Mining Trans. AIME*, vol. 184, pp. 215-223, 1949.

<sup>a</sup> S = satisfactory. S- = Not completely satisfactory. U = Unsatisfactory.

The stoker performance is so complex that it is not reasonable to expect the performance factors to vary with single coal factors; at least two or three coal characteristics are at work at the same time in affecting clinker formation alone.

<sup>1</sup> KAISER, E. R., in a discussion of the Purdy and Nelson paper.

Important factors in determining the degree of satisfaction from a bituminous coal are (1) initial ignition, (2) clinker formation, (3) coke formation, (4) rate of fuel consumption during hold-fire operation, (5) resistance of the fuel bed to the flow of air, (6) uniformity of burning during intermittent operation, and (7) smoke concentration.

### Burning Anthracite on Underfeed Stokers<sup>1</sup>

Small underfeed stokers are available for the combustion of anthracite in domestic ranges of about 15 to 85 lb coal per hr; and in commercial models (Skelly of C-E Co. and Flynn & Emrich) up to 1,000 lb (see section on Underfeed Stokers for Anthracite). While essentially the same as comparable bituminous-coal stokers, there is sufficient difference in design, principally in the supply and admission of air, to make it advisable not to burn anthracite on stokers designed for bituminous coal unless recommended as a result of tests by Anthracite Institute Laboratory.

**Balance between Air and Ash.** The small anthracite stoker is more sensitive to a proper balance between the air supply and the ash quality than virtually any other type of coal firing. If the carbon dioxide is maintained at a higher-than-design level, it will almost always be at the expense of increased combustible in the ash; if attempts are made to burn the ash out completely, excessive air may increase the stack loss. Thus, in setting a stoker of this type, careful attention should be given to the balance between these items, rather than trying to obtain optimum conditions on both points simultaneously.

**Carbon Dioxide.** As in other classes of combustion equipment, a carbon dioxide percentage as high as is compatible with other operating conditions is desirable. However, unless it can be obtained with a reasonably wide (1 to 2 in.) ash ring on the round domestic models, green coal will almost invariably spill over to the ashpit to cause a most undesirable loss. Thus, while an Orsat is useful in locating air leaks, its readings should not be depended upon for air settings without the further consideration of ashpit loss as determined from analyses or observation of the fire. On a domestic stoker of average size, a 1- to 2-in. ash ring is considered desirable; narrower rings waste coal to the ashpit; wider rings waste heat to the stack as excess air. Mulcey<sup>2</sup> gives the following CO<sub>2</sub> and ash figures as a basic range for domestic anthracite-stoker settings:

	Poor	Good
Carbon dioxide, per cent	Below 8	9-12
Combustible in ash, per cent.	Over 40	15-30

**Combustible in Ash.** In addition to the above consideration of setting the stoker by the width of the ash ring, if unburned coal is spilling into the ashpit at one point, or if the burning coal is not symmetrical with the periphery of the retort, it may mean either that the top of the stoker retort is not level or that there is excessive segregation of fines at the retort top. A black spot, such as is frequently seen in the center of a retort, is of little significance unless it is so large as to reduce the effective grate area, or unless it is asymmetrical to a point that green coal is spilling to the ashpit, as above.

**Service Suggestions.** Aside from the more readily diagnosed causes for interruption, such as failure of the coal to feed, and control difficulties, the most frequent causes of substandard results are excessive undersize in the coal, and obstructions to the proper air delivery.

<sup>1</sup> MULCEY, PAUL A., Domestic Anthracite Stokers, *Anthracite Industries Laboratory Bull.* L-37, 1940 (now Anthracite Institute). A Guide for Reducing Fuel Consumption in Commercial Plants, *U.S. Bur. Mines Bull.* 466.

<sup>2</sup> *Op. cit.*

**Undersized coal** may be as caused by excessive segregation in the bin or by poor coal, or it may be the result of excessive grinding in the feed worm. In the latter case, the worm or bottom of the retort may be broken or worn, or foreign materials such as wires or rags may be wrapped around the worm. It is well to insist on stainless-steel coal-feed worm and shafts, unless the construction is such as to use cast iron, since the life of carbon-steel worms and worm shafts is limited to the feeding of as little as 40 tons of coal or even less.

**Obstructions to air delivery** may be caused by dust or foreign material in the air ducts, wind box, or tuyère openings, or they may even be due to inadequate air in the cellar. Certain antifreeze treatments, such as common salt, sometimes have a tendency to cause deposits in the lower part of the tuyères to block the air and cause difficulties.

**Draft.** As is the case with virtually all combustion equipment, maximum efficiency will be obtained with an absolute minimum of furnace draft. Just sufficient negative draft should be maintained at the fire door to prevent positive pressure with resultant discharge of gas and fly ash to the cellar. If the chimney is higher than necessary, a barometric type of draft damper may be used, but ordinarily they are unnecessary with the steady firing rate of small stokers.

**Table 23-9. Burning Rates of Round-stoker Retorts<sup>1</sup>**

Retort diam, in.	Retort area, sq ft	Lb coal/hr/sq ft retort area									
		13	14	15	16	17	18	19	20	21	22
10	0.545	7.1	7.6	8.2	8.7	9.3	9.8	10.3	10.9	11.4	12.0
11	0.660	8.6	9.2	9.9	10.6	11.2	11.9	12.5	13.2	13.9	14.5
12	0.785	10.2	11.0	11.8	12.6	13.4	14.1	14.9	15.7	16.5	17.3
13	0.922	12.0	12.9	13.8	14.7	15.7	16.6	17.5	18.4	19.3	20.3
14	1.068	13.9	15.0	16.0	17.1	18.2	19.2	20.3	21.4	22.4	23.5
15	1.226	15.9	17.2	18.4	19.6	20.8	22.1	23.3	24.5	25.8	27.0
16	1.395	18.1	19.5	20.9	22.3	23.7	25.1	26.5	27.9	29.3	30.7
17	1.575	20.5	22.0	23.6	25.2	26.8	28.4	29.9	31.5	33.1	34.7
18	1.767	23.0	24.7	26.5	28.3	30.0	31.8	33.6	35.4	37.1	38.9
19	1.968	25.6	27.6	29.6	31.5	33.5	35.5	37.4	39.4	41.4	43.3
20	2.180	28.4	30.5	32.7	34.9	37.1	39.3	40.4	43.6	45.8	48.0
21	2.400	31.2	33.6	36.0	38.4	40.8	43.2	45.6	48.0	50.4	52.8
22	2.640	34.3	37.0	39.6	42.3	44.9	47.6	50.2	52.8	55.5	58.1
23	2.880	37.4	40.3	43.2	46.1	49.0	51.9	54.8	57.6	60.5	63.4
24	3.142	40.8	44.0	47.1	50.2	53.4	56.5	59.7	62.8	66.0	69.1

**NOTE:** Figures in body of table show total pounds per hour for retorts of the several sizes at the burning rates shown at the top of the columns. Multiplying these figures by 29 gives the maximum rating in terms of steam radiation (240 Btu per sq ft) as specified by Commercial Standard CS48-34.

<sup>1</sup> MULCEY, PAUL A., Domestic Anthracite Stokers, *Anthracite Institute Bull.* L-37, 1940.

**Baffles for Small Underfeed Anthracite Stokers.** The use of overfire baffles for small underfeed anthracite stokers is highly desirable in most instances in order to reduce furnace exit-gas temperatures and thus increase efficiencies. Most boilers in which such stokers are installed were designed for considerable side-wall absorption of heat. This is largely lost with stoker firing unless the gases of combustion can be brought into closer contact with the side walls by such devices as baffles.

Three types of baffles are in most common use: (1) curtain baffles for rectangular boilers which force the gases down under a suspended curtain after sweeping the crown sheet, (2) downdraft tubes which perform similarly, and (3) suspended refractory or metal plates or cones. Anthracite Institute has found<sup>1</sup> that the shape, type,

<sup>1</sup> Baffles for Stoker Fired Boilers, *Anthracite Institute Bull.* L-38, 1940.

and location of a baffle are secondary to the extent to which it causes the gases actually to sweep side walls or other furnace surfaces.

Thus a round suspended baffle is shown to be of little use unless its size is such that it forces side-wall impingement (see Table 23-10). In general, a baffle should be designed to bring the boiler draft resistance up to a total of about 0.1 in.  $H_2O$ . The gain through the use of the baffle will be proportionate to the extent to which the unbaffled boiler resistance fell below 0.1 in. with a maximum probable increase in output of about 12 per cent.

**Table 23-10. Recommended Sizes of Round Suspended Baffles<sup>1</sup>**

(For round furnaces of various diameters and having various unbaffled draft resistances. Body of table shows baffle size)

Draft resistance, in. $H_2O$ . . .	0 10	0 08	0 06	0.04	0.02
Per cent area baffled . . .	70	75	80	85	90
Boiler diam, in. <sup>a</sup>					
10	8¼	8¾	9	9¼	9½
12	10	10½	10¾	11	11¼
14	11¾	12¼	12½	13	13¼
16	13½	14	14¼	14¾	15¼
18	15	15½	16	16½	17
20	16¾	17¼	18	18½	19
21	17½	18¼	18¾	19½	20
22	18½	19	19¾	20¼	21
23	19¼	20	20½	21¼	21¾
24	20	20¾	21½	22¼	22¾
25	21	21¾	22½	23¼	23¾
26	21¾	22½	23¼	23¾	24¾
27	22½	23¼	24	24¾	25½
28	23½	24¼	25	25¾	26¾
29	24¼	25¼	26	26¾	27½
30	25¼	26	26¾	27½	28½
32	26¾	27¾	28½	29½	30¼
34	28½	29½	30½	31¼	32¼
36	30¼	31¼	32¼	33¼	34¼

NOTE: Though sizes are shown as calculated, it will be more practical to use nearest even inch for actual size.

<sup>1</sup> *Anthracite Institute Bull.* L-38, 1940.

<sup>a</sup> As measured at point of location of proposed baffle.

Table 23-11 shows the baffle size expressed in terms of full furnace area, which can be safely used without undue increases in draft restriction. This table also shows the probable increase in boiler output to be expected if *this full-sized baffle is used*. If a smaller baffle is selected, improvement will be proportionately less.

**Table 23-11. Baffle Design Chart<sup>1</sup>**

(For suspended metal or refractory baffles)

Draft resistance through boiler, in. <sup>a</sup> . . .	0.02	0.04	0.06	0.08	0.10 <sup>b</sup>
Baffle size recommended, per cent of grate area.	90	85	80	75	70
Probable increase in output, per cent. . . . .	12	10	8	4	2

<sup>1</sup> Baffles for Stoker Fired Boilers, *Anthracite Institute Bull.* L-38, 1940.

<sup>a</sup> Breaching draft (inches  $H_2O$ ) with zero furnace draft as measured *before* baffle is installed.

<sup>b</sup> Benefit of baffle doubtful if unbaffled boiler draft resistance exceeds 0.10 in.  $H_2O$ .

Refractory baffles are used extensively, but difficulty of installation and access makes it difficult to use sufficiently large sizes; thus most such baffles are found installed in grossly inadequate diameters.

A further advantage of furnace baffles is their effect in reducing fly ash, because they deflect from 50 to 85 per cent to the ashpit.

### Domestic Stoker Control

The accepted method of controlling domestic stokers has been by means of a room thermostat as protected by safety switches and as supplemented by a hold-fire control, of the thermostatic or timing type, for mild weather. As long as the thermostat called for heat, the stoker ran, unless interrupted by a safety switch. A resultant disadvantage was that, in prolonged operation on caking bituminous coals, troublesome coke trees formed to interfere seriously with the orderly process of combustion.

**Thermo-interruption Fire Pilot.** To alleviate this condition, Sampsel Time Control, Inc., has introduced a new idea in control in which the thermostatic call is interrupted once every 15 min for a length of time adjustable up to 7 min out of each 15.

This halt allows the fire to "catch up" with the raw-coal feed, thus allowing higher and more efficient rates of coal feed with more uniform fires. The higher feed rates also compensate for the feed lost during the artificial shutdown periods. Coke trees formed during the burning period are weakened by combustion at the base during the stop period, to topple and burn.

Sampsel claims to have burned successfully a wider variety of coals than has heretofore been considered practical. However, they caution that the control will not overcome such undesirable coal properties as excessive ash or low ash-fusion temperatures, but they consider thermo-interruption a substantial aid to better operation and increased economy.

### MULTIPLE-RETORT STOKERS<sup>1</sup>

Multiple-retort stokers are an extremely popular method of burning caking free-burning bituminous coal, particularly in the approximate size range of 25,000 to 200,000 lb steam per hr. A survey conducted by Appalachian Coals, Inc.,<sup>2</sup> in 1935 showed that underfeed stokers were firing 30 per cent of the boilers of the United States, accounting for 60 per cent of the coal mechanically fired, and that the multiple-retort type, in turn, accounted for 32 per cent of the underfeed stokers.

**Principle of Operation.** Multiple-retort stokers are constructed in three distinct sections to handle the three successive burning stages of caking bituminous coal, caking and combustion of the volatile, burning of the formed coke, and final burning of the refuse. The first section consists of a number of parallel sloping retorts into which coal, as discharged from the hopper, is pushed by rams to the lower edge. The second section, located immediately below the first, consists of a number of reciprocating plates designed to receive, burn, and convey the broken coke and unagglomerated material formed in the first, or retort, section. This second section is known as the overfeed or extension-grate section. The third section is a dead plate of the continuous or dumping type or rotary ash discharge, designed to hold the nearly burned out material until it can be either completely consumed or discharged to the ashpit (Fig. 23-7 b).

**Air Zones.** A method is usually provided for zoning the air under the grates into two or more compartments. The exact method and number of compartments vary

<sup>1</sup> DE LORENZI, OTTO, "Combustion Engineering," Combustion Engineering-Superheater. Inc., New York, 1947.

<sup>2</sup> Fairmont Coal Bureau, *Reference Bull.* 8, August, 1946.

with the manufacturer and size of stokers but almost always include provision for different air supply to the retort, or tuyère, section and the overfeed, or extension-grate, section. On the wider stokers, in particular, lateral zones may also be provided

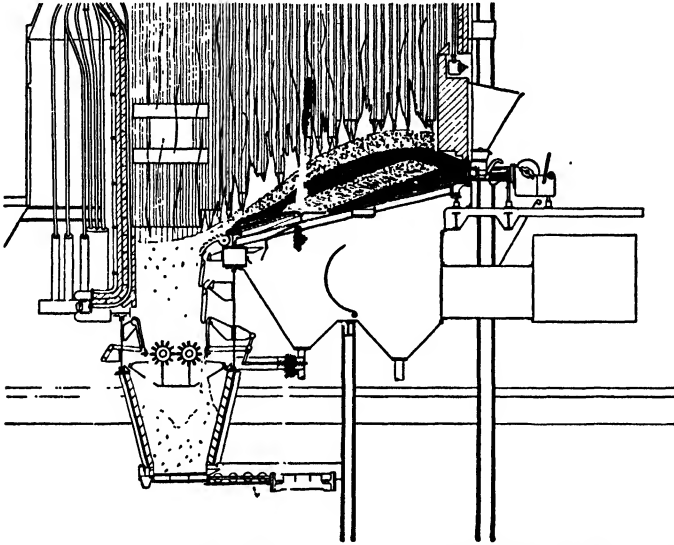


FIG. 23-7a. New model R Riley superstoker. Riley-Badenhausen steam generating unit.

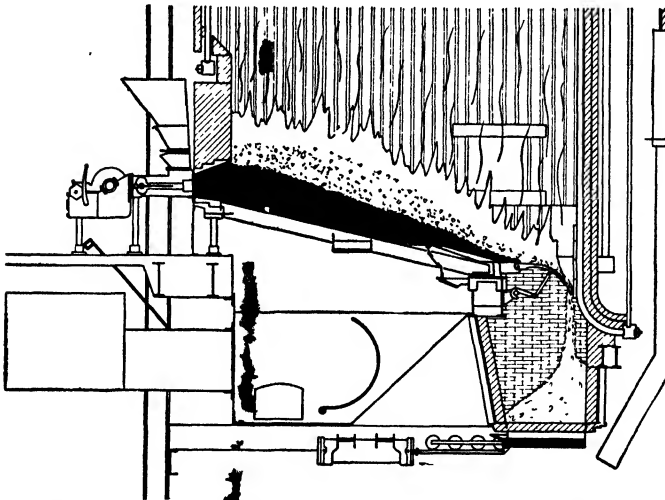


FIG. 23-7b. New model R Riley superstoker. Riley-Badenhausen boiler. Riley-Badenhausen water-cooled furnace.

to compensate for inequalities in the feeding of the coal or segregation of sizes in the hopper. Lateral zoning is also valuable to correct uneven lateral fuel-bed conditions.

**Types of Ash Removal.** Three distinct types of ash removal are available:

1. **Dump type**, in which the hinged dead plate is operated intermittently as dictated by the condition of the fire



2. **Continuous-discharge type**, in which the surface of the grate is somewhat, if not completely, similar to the manual dump type, but in which the dumping is performed automatically by continuous mechanical motion

3. **Rotary ash-discharge type**, in which a set of slowly revolving rolls, located at the rear of the stoker, receives, grinds, and discharges ash to the pit

**Selection of Ash-discharge Type.** Generally the coal, the size of the stoker, and the character of the expected load will determine whether the clinker-grinder, continuous-ash-discharge, or dump-grate type of construction should be used. Large stokers, high-ash coals, continuous operation at high capacity, or a combination of these factors will indicate the desirability of the use of **grinders**. They contribute to reduced carbon losses, better furnace condition, and higher CO<sub>2</sub> content of furnace gas.

Next in order of choice is the simple, but hardly less effective, **continuous-ash-discharge type**. This design is capable of practically the same performance as the grinder type, but a more careful supervision is required. The comparable efficiency is somewhat lower, because of a small increase in ashpit carbon loss due to the limited time available after the refuse leaves the extension section. Both the clinker-grinder and the continuous-ash-discharge types require the installation of water-cooled surface in the rear furnace wall. They also require relatively deep ashpit space.

**Dumping grates** are used in smaller units and with low-ash coals where intermittent dumping will not interfere with the load. They are also widely used in conversions on account of shallow ashpits and the fact that rear-wall water cooling, while desirable, is not necessary. More manual labor is required as the dump plates must be raised and lowered periodically. There may be a momentary drop in capacity, as well as in CO<sub>2</sub> during dumping. Furthermore, some of the live fuel on the extension-grate section may slide into the ashpit during dumping. As a result, efficiency is lowest with the dumping type of ash removal.

**Fuel-bed Characteristics.** The fuel bed on a multiple-retort stoker is of two distinct types. In the underfeed section there are parallel rows of hills and valleys, extending from the front wall to the discharge end of the retorts. The hills occur over the relatively inactive retort areas, because they have no provision for air admission. The coal is supplied by a reciprocating feed, and this produces a certain amount of segregation in the fuel bed. The coarse coal finds its way to the tuyères near the front. The fines travel the length of the retort. No lateral motion is provided to feed the coal directly onto the adjacent tuyères. The stroking action of reciprocating secondary rams partly agitates the high ridges of ignited, smoldering, and partly caked coal over each retort. This produces a limited amount of lateral feed, which supplies fuel to the tuyère zone.

High combustion rates and a thin active fuel bed exist over the tuyères through which the air is admitted. To shake down and level out these alternately thick and thin parallel ribbons is the function of the overfeed section. As this irregular mass of burning fuel reaches the overfeed section, which usually equals some 20 to 30 per cent of the length of the underfeed section, it is quickly shaken down to uniform thickness by the reciprocating action of the grates in this area. The fuel bed is now level, compact, homogeneous, and extremely active because of the stoker control and the admission of correct air quantities. As a result, the fuel bed may be burned out uniformly across the stoker width by the time the fuel reaches the dump grates or ash-discharge section.

#### **Relation of Furnace Design and Fuel Specifications to Performance of Multiple-retort Stokers**

In a multiple-retort stoker installation, the degree of approach to optimum efficiency and operating conditions depends to a very marked extent upon such factors as:

1. Construction of the stoker, with particular respect to such items as ash discharge and air control.
2. Construction of the furnace, with reference to such items as furnace volume, air turbulence and side-wall construction.
3. Selection of the coal, with particular reference to its adaptability to the conditions of stoker and furnace design, plus such additional items as the load to be carried and the rate of load fluctuation.

Each of these major considerations is interlocked with the others to a point where either a complete coordination of design, operation, and coal selection must be made or a compromise effected to meet properly any existing less than ideal phases of the three.

**Ideal Conditions of Design and Operation.** Hypothetical conditions such as might be specified in the unusual and improbable circumstances of an engineer's having complete control of equipment design, operating characteristics, and fuel selection would probably include:

1. A furnace volume to give a heat liberation of not over 35,000 Btu per cu ft of furnace volume per hr.
2. Sufficient furnace turbulence to ensure thorough mixing of all lean and rich gases arising from the fuel bed.
3. Sufficient side-wall cooling to prevent the adhesion of clinker.
4. Use of a caking bituminous coal in a 2-in. nut and slack size in which not over 50 per cent of the slack content will pass through a  $\frac{1}{4}$ -in. round-hole screen. The coal to be uniformly distributed across the stoker hopper, to have a volatile content between 20 and 30 per cent, an ash content between 6 and 8 per cent, an ash-softening temperature above 2400°F, and an iron content ( $\text{Fe}_2\text{O}_3$ ) of the ash of not more than 15 per cent.

### Furnace Design

**Furnace Volume.** Ample furnace volume facilitates higher sustained capacities with a minimum of effort and maintenance. It is also a major consideration in reducing difficulties in new installations, so that, whatever, the compromise on other factors, furnace volume should not be sacrificed. Optimum is 35,000 Btu per cu ft of furnace.

**Overfire Air.** While there is really no solution to a material restriction of furnace volume other than the installation of a modern unit of integrated design, when such a restriction does exist, as on the older installations, the use of overfire air may improve conditions somewhat.

A recommended method of overfire-air supply is the discharge of relatively high velocity air, such as at pressures of from 10 to 30 in. water, through a number of jets located in the furnace bridge wall. Rear-wall jets have been found to be far more effective than a large number of low-velocity openings in the front furnace walls. As furnaces usually contain adequate air for combustion, the action of the jets is largely one of setting up sufficient turbulence to mix the furnace gases thoroughly and thus ensure their proper combustion. For this reason, steam may be satisfactorily substituted for air whenever more desirable. Furnace turbulence also serves to reduce the fly-ash carry-over.

**Side-wall Cooling.** Inadequate furnace volume also frequently leads to side-wall clinker adhesion. As combustion progresses, such clinkers grow to become a potential cause for serious grate burnouts. The installation of water-cooled surfaces at the stoker side walls serves to minimize this difficulty with materially improved operating conditions. Air-cooled walls and carborundum brick are also frequently used for the

same effect. In the latter case, the results are somewhat proportionate to the degree of the difficulty encountered.

**Rear Arches** (as for nonagglomerating coals). Coals lacking in tendency to agglomerate, and thus not forming satisfactory coke masses, have a tendency to drift; *i.e.*, partly ignited and green coal will blow or drift to the discharge end of the stoker to result in generally unsatisfactory operation and high maintenance. Just as is the case with traveling-grate stokers, the obvious solution is the addition of a long rear arch to cause a redeposit of the drifted coal to the front end. Such arches also provide turbulence. Short rear arches usually fail to produce maximum possible improvement.

**Preheated Air** (and furnace maintenance). Based upon a record of a large number of installations, reasonably low maintenance costs require that the combustion-air temperature shall not exceed 250 to 300°F. An average of many installations showed furnace maintenance costs of 3 cents per ton of coal with 200°F air; 6 cents per ton with 300°F air; and 14 cents with 400°F air. In seeming contradiction, one large plant reported furnace maintenance of 3.2 cents with 330°F air. However, the latter was with skillfully maintained fuel-bed contours and careful coal selection and thus serves to illustrate the importance of operating adjustment and coal characteristics on the item of maintenance.

**Air Distribution.** It is important that air distribution be uniform and that it give maximum cooling to all parts of the grate surface. With either manual or automatic regulation, air flow should not be reduced to an extremely low rate or shut off completely just after carrying an active fuel bed. This precaution is of especial importance when low-ash coals are burned, because the lower end of the grate has very little protective ash covering.

**Air Control.** Sectionalized control of the air from the front to the rear of multiple-retort stokers permits different pressures under various sections of the grate. A higher pressure may be used if the fuel bed is too thick, while a reduced pressure may be used at the thinner areas. Usually, with a satisfactory fuel-bed contour, the air is uniform over the entire retort section and slightly lower under the overfeed or extension-grate area.

### Fuel-bed Contour or Control

The best general guide for multiple-retort operation is the fuel-bed contour. The depth above the tuyères should be sufficient to hold excess air flow to a reasonable level. Experience indicates that with the freer burning coals the depth should be between 14 and 16 in., and with the higher coking coals between 22 and 24 in. Where large coke masses form, there are usually accompanying crevasses which permit the flow of excess air. By increasing the fuel-bed thicknesses, it is possible to minimize the relative area of the crevasses and thus effect more uniform air distribution. A freer burning coal, forming smaller coke masses, will give a thinner more uniform fuel bed, with more satisfactory operating conditions. With coals containing a large percentage of lump, it may be necessary to carry thicker fuel beds than with slack.

If the fuel bed is generally too thin, increasing the speed of the stoker rams will thicken it. If the fuel bed tends to become too heavy at the front end, an increase in the length of the stroke of the secondary rams is necessary. The lateral contour may be adjusted by means of individual controls on each secondary ram where the same have been provided.

Over the extension grate, the fuel bed should be 6 to 8 in. deep for the freer burning coals, and 8 to 10 in. deep for coals of greater caking quality. A thin bed of burning fuel and refuse on the discharge plates, or a sloping level over the clinker grinder pit, gives the best over-all results.

### Fuel Specifications

**Effect of Coal Sizing.** Coal specifications for multiple-retort underfeed stokers usually call for 2-in. nut and slack with not more than 50 per cent of the slack through a  $\frac{1}{4}$ -in. round-hole screen, and for the fuel to be delivered across the hopper without segregation. Best results are obtained when there is a uniform gradation in coal size from lump to slack. Excessive fines make it necessary that a higher percentage of the burning process be carried out in the overfeed section. This results in localized high combustion rates, with a resulting increase in carbon loss. Readily accessible adjustments are provided to maintain a most suitable contour of fuel bed regardless of fuel-size variations.

**Volatile Content.** Figure 23-8 shows typical performance curves for two volatile ranges, 15 to 25 per cent, and over 30 per cent. In general, coal with 20 to 30 per cent

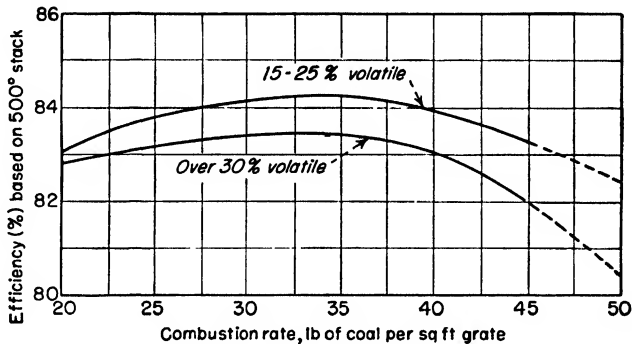


FIG. 23-8. Typical performance curves for multiple-retort stokers. NOTE: As the above efficiencies are as for 500°F exit gas temperature, a correction factor of approximately 3 degrees per 100° variation from this temperature should be applied. (de Lorenzi, Otto, "Combustion Engineering," *Combustion Engineering-Superheater, Inc.*, New York, 1947, p. 4-17.)

volatile is recommended, with marked decreases in efficiency to be expected when the volatile exceeds 30 per cent. In areas where smoke is an important item, it may be necessary to use even a lower volatile particularly with dump grates.

**Ash Analysis.** While by no means infallible, the ash-fusion temperature and per cent  $\text{Fe}_2\text{O}_3$  will generally serve as a good indicator of the clinkering qualities of a coal.  $\text{Fe}_2\text{O}_3$  usually averages much higher when the ash-fusion temperature is low. There are some coals, however, in which the  $\text{Fe}_2\text{O}_3$  ranged from 10 to 14 per cent with corresponding ash-fusion temperatures of 2100 to 2400°F. In others, with  $\text{Fe}_2\text{O}_3$  of 20 to 24 per cent, the ash-fusion temperature was from 2500 to 2750°F. Nevertheless, where exceptions have not been established, it is considered desirable to keep the  $\text{Fe}_2\text{O}_3$  below 20 per cent with the high-fusion ash coals, and below 15 per cent with coals of lower ash-fusion temperatures.

In general, coals should be selected with relatively low ash contents. However, there are a number of free-burning coals with relatively high ash content whose softening and clinkering characteristics will allow agitation and which may thus be burned satisfactorily on multiple-retort stokers.

**Blending Coals.** Some attempts have been made to improve coal quality by blending. A mixture of a low-ash coal, a high-ash coal, and a drifting coal may give more satisfactory results than any one of the coals alone. However, considerable study and actual tests are necessary to justify the expense of mixing and the care required to prevent segregation.

**Agglomerating Characteristics.** Coals that have a tendency to cake, but break into a porous fuel bed when agitated, are most suitable for multiple-retort stokers. Nonagglomerating coals have a tendency to drift to the rear of the stoker; and highly caking coals may not produce so satisfactory a fuel-bed contour.

**Coal Cost as a Factor in Selection.** When a stoker plant is located at a considerable distance from the coal fields, the comparative delivered prices of various coals are usually not far apart. The selection of the coal best suited may be made on a basis of comparative burning tests. However, when the plant is closer to the mines, the choice is more difficult. The cheapest coal may be one that causes high grate maintenance or considerable operating difficulties. In such cases, the balance between coal costs, increased maintenance, and operating difficulties must be carefully worked out. Sometimes the highest priced coal will be the most economical.

### Fuel-burning Rates on Multiple-retort Stokers

Combustion rates on the multiple-retort stoker grate may be limited by a number of factors or a combination of factors, such as cinder emission, slow ignition and penetration, excessive furnace temperatures, cinder adhesion to the walls, and drifting of the fuel to the rear of the stoker. More often, however, the formation of troublesome clinkers, difficult to remove, is the limiting factor. Such clinkers also affect the distribution of air to the grate surface, causing excessive ashpit losses and high maintenance.

According to "Combustion Engineering," satisfactory operation is obtainable with combustion rates of about 40 lb of coal per sq ft per hr for a continuous rating and a peak rating of under 60 lb. These values are for the continuous-discharge and clinker-grinder types of stokers; the dump-grate stokers will approximate about 85 per cent of these values.

For high-ash low-fusion-ash coals and for drifting coals, lower combustion rates are desirable, probably around 35 lb per sq ft of grate per hr for continuous ratings. Thicker tuyères with larger air openings seem to offer some advantages for the low-fusion-ash coals.

**Balance between CO<sub>2</sub> and Ash Burnout Desirable.** In calculating a heat balance to determine the over-all efficiency of a proposed steam-generating unit, a comparatively high percentage of CO<sub>2</sub> or low excess air for a given exit-gas temperature will naturally give the highest efficiency. In daily operation, however, even where the furnace volume is ample, a moderate CO<sub>2</sub> with well-burned-out ash will usually give the most satisfactory results from a balanced standpoint of efficiency, reliability, and maintenance.

**Table 23-12. Typical Performance Data of Multiple-retort Stokers<sup>1</sup>**

Duration, hr .....	22 01	21 04	13 34	10 83
Actual evaporation/hr, lb.....	115,580	117,721	194,561	195,092
Coal burned/hr, lb.....	11,223	11,532	19,812	19,912
Coal/sq ft grate/hr, lb.....	22 9	23 6	40 4	40 7
Drum pressure, psia .....	213 5	213 5	215 1	214 4
Temperature, water to boiler, deg F	121 7	120 2	120 7	124 9
Temperature, gas from boiler, deg F <sup>2</sup>	501	505	603	606
CO <sub>2</sub> stack gas, per cent .....	15 52	14 96	15 73	15 17
Moisture in steam, per cent ..	0 05	0 06	0 17	0 17
Heating value of coal as fired, Btu.	13,540	13,470	13,411	13,329
Heat absorbed by boiler, per cent	84 30	84 10	81 19	81 18

DATA: Washington, Central Heat Plant; boilers 25,243 sq ft each; 15-retort stokers, each having a projected area of 490 sq ft; rear and side walls have 1,316 sq ft water-cooled surface; volume combustion space 9,435 cu ft. Designed for 82 per cent efficiency at 113,000 lb per hr equivalent evaporation.

<sup>1</sup> DE LORENZI, OTTO, Combustion Engineering," p. 4-17, Combustion Engineering-Superheater, Inc., New York, 1947.

SPREADER STOKERS<sup>1</sup>

The spreader stoker is probably capable of burning coals of a wider differing analysis than any other type. It has its greatest acceptance where the load to be carried may be variable but is to a considerable degree constant. Its thin fuel bed makes it suitable for the use of coals of high ash and volatile content because of the absence of clinkering. It burns considerable of the fuel in suspension, allowing the heavier particles to be deposited on the grate for slower burning. Since the fuel bed is usually only 2 to 4 in. deep, the spreader stoker does not operate satisfactorily under intermittent control. It must be modulated automatically if satisfactory operation is to result.

Spreader stokers were one of the earliest methods of firing solid fuels, with the patents dating back to 1822. For reasons of economy, the earlier stokers were of the natural-draft type; and the necessity for adequate furnace volumes and accurate combustion control had not been recognized. As a result, the earlier units were characterized by objectionable fly-ash carry-over, excessive smoke emission, and generally disappointing operation.

By reason of these seemingly inherent disadvantages, the spreader stoker almost disappeared from the market until, in 1925, a redesigned spreader stoker was introduced with more efficient feeding and distributing mechanism, and with the inclusion of forced draft and a high-resistance grate surface. Developments since that date have been so rapid that the spreader stoker now ranks high among modern methods of burning a wide range of solid fuels.

**Principle of Operation.** In the forced-draft spreader stoker, feeding and distributing mechanisms continuously project coal into the furnace above a grate of either the stationary, dumping, or traveling continuous-discharge type. The fines are partly burned in suspension, while the larger particles are burned without agitation but in an intensely active condition on the grate. The spreader stoker thus combines some of the principles of the firing of pulverized coal and the combustion of coal on grates.

**Types of Feeders Employed.** In carrying out the general principles of the spreader stoker, various methods have been employed for throwing or spreading the coal. These include such devices as: the paddle-type underthrow spreader, in which the paddles revolve so as to throw the coal into the furnace from their bottom periphery; the paddle-type overthrow spreader, in which the paddles revolve so as to throw the coal from the top point of their periphery; air jets, in which the coal is conveyed and distributed by air from some convenient coal-hopper and fan location; and a method of spreading the coal with a steam jet, in which the coal is brought from the hopper to the jet with an adjustable screw feed. (Jet-type stokers are characteristically used on locomotives.) In all types, particular attention is given to ensuring as even distribution of the fuel over the entire grate area as is possible. This is accomplished by such means as tilting the paddles at different angles, setting alternate blades in different directions, and curving the blades so that the direction will be influenced by the point of impact. Various methods of feeding the coal to the paddles are employed, usually of measuring or metering types.

**Stationary-grate Spreader Stoker.** A typical spreader stoker consists of coal-feeding units spaced above the grate line and located on the front wall of the furnace. These units include a variable-feeding device for conveying coal to a rotor or rotors on which the blades are mounted. These revolving blades of the feeder strike the

<sup>1</sup> BEERS, R. L., Recent Developments in Spreader Stoker Firing, *Mech. Eng.*, vol. 64, No. 12, pp. 867-971, 1942. DE LORENZI, ORTO, "Combustion Engineering," Chap. 5, Combustion Engineering-Superheater, Inc., New York, 1947. BARKLEY, J. F., U.S. Bureau of Mines, The Forced Draft Spreader Stoker, *Trans. ASME*, May, 1937, pp. 259-265.

incoming fuel and throw or sprinkle it uniformly over the entire grate area which, in this model, consists of horizontal grates, usually with forced draft. The design of the feeder is of paramount importance, for upon it depends the ultimate uniformity with which the coal is burned.

The finer particles of coal are burned either wholly or partly in suspension, and the coarser particles are burned on the grate. The air openings in the grate surface are usually restricted to less than 5 per cent of the total grate area to minimize the effect of relatively wide variations in the fuel-bed and ash-bed resistances as the grate loads after cleaning, and also to increase air velocity to promote turbulence and rapid burning. As the fresh coal is thrown on top of the live fuel bed ignition is very rapid. The ash, which is always at the bottom of the fuel bed, is chilled by the incoming air, thus tending to reduce the formation of clinker and also acting as a heat insulator to protect the grates. It is not necessary to disturb the fuel bed which would promote the formation of clinker and overheating of the grates.

With ordinary stationary-grate operation the fires should be cleaned after the ash has accumulated to a depth of 4 to 6 in. In turn, the grates should be so proportioned that this is not oftener than every 4 hr with normal loads.

**Power-operated Dumping Grates with Spreader Stokers.** Where a more rapid cleaning of the fires is desired than is possible with stationary grates, power-operated dumping grates may be employed. In contrast with the earlier undivided plenums under the grate, the air chamber or ashpit is now typically divided to provide a separate chamber for each feeder and for each section of the grate. In cleaning, one section of the air and coal supply can be cut off without interfering with the other sections, thus reducing excess air in the furnace.

With power-operated grates it should be possible to clean a section in 2 to 3 min.

Spreader stokers with power-operated dumping grates have produced very satisfactory results with boilers having a capacity of 100,000 lb steam per hr and even larger.

**Continuous-discharge Spreader Stokers.** On still larger boilers where it is desirable to eliminate all varying fuel-bed conditions, such as variations in the depth of ash and the interruptions of cleaning, a continuous-discharge traveling grate is employed.

With large boilers containing several sections of grate and several feeders, interruptions for cleaning can prove quite serious, particularly where the coal has a fairly high ash content. Whereas, with a low-ash coal, cleaning might be required only once in 8 hr or more, with some high-ash fuels, cleaning would possibly be necessary once every hour, unless a low rate of combustion was maintained.

To overcome this deficiency, a continuous-cleaning grate of the traveling type has been incorporated with the spreader stoker with noted success. Reversing the orthodox traveling-grate principle, this grate travels forward at slow speed to discharge the ash at the front of the boiler.

As the spreader-stoker grate has to travel forward only fast enough to discharge the ash without regard to the coal feed, the movement is considerably slower than with the conventional traveling-grate stoker. For an average installation using a coal containing 8 per cent ash and burning 60 lb coal per sq ft of grate area per hr, Beers cites a speed of approximately  $\frac{3}{8}$  in. per min. This speed ensures ample ash insulation to keep the grate casting at temperatures of not over 50°F above the boiler-room temperature.

With forward grate travel, the rear end of the grate can be sealed off, which is desirable as the fuel cannot always be thrown the same distance. With excess air admitted through the front of the grates for burning the fine particles of coal in suspension, the ash discharged from the grate is practically free from combustible matter. Tests reported by both Beers and the U.S. Bureau of Mines showed a

"combustible in the refuse" range of from 3 to 17 per cent with resultant losses due to this source of from 0.4 to 3.1 per cent (bituminous and lignite tests only, as anthracite was higher).

Power required for both the grates and feeders is reported at  $\frac{3}{8}$  hp per net ton of coal fired.

Despite the restricted grate openings, air pressure under the grates seldom exceeds 2 in. of water.

**Selection between Intermittent- and Continuous-discharge Types.** According to "Combustion Engineering," an intermittent type of spreader is definitely indicated when the ash in the coal to be burned is less than 7 per cent, and the continuous-discharge type should be used when the ash content is greater than 10 per cent.

#### **Advantages of Spreader Stokers.**

1. A wide variety of coals can be burned at very high rates.
2. Inferior grades of fuel having high and low ash-softening temperatures can be handled more satisfactorily than on other types of stokers.
3. Fuels can be burned that cannot be handled satisfactorily on other types.
4. The fuel burns practically as fast as it is fed into the furnace.
5. A change in the ratio of the coal and air supply almost instantly changes the carbon dioxide content of the flue gases. Spreader stokers are thus characteristically quick in their response to changes in the demands for steam as well as to wide variations in the connected load.
6. The maintenance of the grates is low because the temperature of the iron in the grates is approximately the temperature of the incoming air as soon as a layer of ash is formed.
7. Coking coals burn without the formation of coke because of the thin fires and rapid combustion, together with the fact that the volatiles and tarry hydrocarbons tend to burn first while in suspension to leave material of a less coking nature to burn on the grates.
8. Spreader stokers are less dependent upon coal sizing, particularly uniformity of sizing. Screenings, small run-of-mine, and nut and slack are ideal.
9. The ash is practically free from clinkers and has a low carbon content.
10. The boilers can be put on or taken off the line quickly, thus increasing flexibility and reducing stand-by losses.
11. Quick changes can be made from one fuel to another.

**Disadvantages of Spreader Stokers.** While the disadvantages of spreader stokers are far outweighed by the advantages, they do include the necessity for careful design and proportioning if difficulties are to be avoided from fly ash, smoke, and control.

Fly ash is the major problem with spreader stokers. As the coal is introduced in suspension, fly-ash and cinder carry-over must be taken into consideration in designing the layout.

The fly ash is usually coarse and easy to separate. The combustible content may vary from practically zero, as in the back chamber of a horizontal-return tubular boiler, to as much as 85 per cent in cases where there was little aftercombustion as in the bottom of the second pass of a vertically baffled boiler. With vertical baffles there is more of a tendency for the fly ash to enter the boiler than with horizontal baffles because, with the latter, considerable ash drops behind the bridge wall.

Anthracite and semianthracite usually give more fly-ash carry-over than some of the lower rank coals.

Fly ash should not be allowed to accumulate too much at any one spot, such as at the bottom of the breeching, because it may suddenly lift all at once and go out the stack, causing considerable nuisance.

Fly-ash recovery methods include low-draft-loss cinder traps which frequently give



satisfactory results on natural-draft stokers. However, for induced draft, a cyclone trap or cinder-separating fan will prove most effective. As much of the fly ash will burn when injected into the furnace, reinjection is the rule. In addition to the resultant economy, the nuisance of the fly ash is reduced thereby. Steam jets have been used for returning the fly ash, often with somewhat less than satisfactory results because of operating costs and maintenance problems. High-pressure fans are preferred by many; both have the added advantage of increasing furnace turbulence.

With cinder recovery, and under favorable conditions, heat loss from cinder carry-over can be reduced to 2 or 3 per cent. Without cinder recovery and under unfavorable firing conditions, it may be as high as 12 per cent.

It has sometimes been possible to eliminate fly-ash complaint by screening out sizes below No. 12ASTM screen, and also by oil-treating the coal.

**Controls.** The spreader stoker is so sensitive in its operation that it responds almost instantly to changes in the ratio of air and coal supply. This can prove to be either an advantage or a disadvantage—an advantage if, through proper quick-acting controls, advantage is taken of this inherent ability to follow the fluctuations in the boiler load; a disadvantage if manual control is attempted with resultant tendency to smoke when out of adjustment in one direction and to waste fuel because of excess air in the other.

It is therefore almost essential to provide good automatic-control equipment to maintain the proper draft and ratio of coal to air with fluctuations in the load.

One type of control uses an auxiliary or secondary control to maintain a constant volume of air from the fan through the fuel bed for every main fuel-air setting. This secondary control may be actuated by the drop in pressure across the orifice in the main air duct or by any differential pressure that varies with the main air flow.

In this type, the boiler damper operates directly from the pressure in the combustion chamber and is independent of the main controls.

Another simpler type eliminates the auxiliary control by operating the boiler damper direct from the steam-line pressure; the forced-draft fan operates direct from the pressure in the combustion chamber.

With all such controls, some hand adjustment may be necessary when the coal size is changed appreciably.

**Smoke** can be produced quickly if too much coal is fed into the furnace for the amount of air supplied. Likewise the smoke can be quickly eliminated by increasing the ratio of air to coal, assuming that the heat release is not excessive or the combustion rate too low for maintaining ample furnace temperature.

It is thus desirable to have a smoke indicator. This may range from a simple mirror or periscope to the electronic types which actuate audible or visual signals or even regulate the dampers at set points of "haze" or smoke.

**Furnace Design.** In spreader-stoker firing, the temperature and velocity of the gases entering the boiler section are critical as they are closely related to the fly-ash carry-over. They are also a factor in determining the abrasion of furnace walls and boiler parts.

Barkley recommends a minimum of 14 ft of flame travel, and that such flame travel be horizontally across the grate if possible, in all cases where bituminous or lower rank coals are to be used.

Furnace temperatures of not over 2400°F are desirable; 2000°F is considered a desirable standard for gases entering the boiler passes.

It is important to provide ample combustion space with spreader stokers. Heat releases of from 20,000 to 35,000 Btu per cu ft of furnace volume per hr are the accepted design standards. While higher releases are possible, they are very likely to produce excessive smoke.

De Lorenzi writes that "for suitably water-cooled furnaces this rate can be stepped up to 40,000 to 45,000 Btu/cu ft/hr." However, this would seem to warrant the caution of very careful design, coal selection, and operation.

Deep ashpits with basement removal are always desirable, and are essential for grates over 12 ft long unless, of course, mechanical ash conveyors are used.

At present a 16- to 20-ft throw of the coal is considered a maximum, with Combustion Engineering Co. reportedly filling a number of orders for the latter size.

There is no limit to the width of spreader stokers, except insofar as boiler design and costs are affected.

**Efficiency Compared with Underfeed Stokers.** In general, and with suitable coals, the spreader stoker may be expected to show about the same over-all efficiency as the underfeed stoker. All items of heat balance are virtually parallel, with the exception of the carbon loss in the fly ash, where not returned to the boiler. On the poorer coals, the spreader stoker is at a distinct advantage. Under regular operating conditions, in general, the firemen will more nearly approach test efficiencies with the spreader stoker than with the underfeed stoker.

**Efficiency Compared with Pulverization.** The efficiency of pulverized fuel may be expected to exceed that of the spreader stoker by a few percentage points. However, and particularly in the smaller and medium installations, this is likely to be offset by the lower auxiliary power and lower maintenance of the spreader stoker.

The spreader stoker is apparently establishing a preference over pulverized-fuel units, at least for capacities up to 200,000 lb steam per hr.

**Maintenance.** Maintenance of continuous-discharge spreader stokers is very moderate owing to the low speed and low temperature of the traveling grate and to the fact that the firing mechanism is located outside of the furnace.

Bowman<sup>1</sup> reports average costs of grate maintenance of 4.22 mils and of stoker maintenance of 5.26 for a total of 9.48 mils per ton of coal fired for 37,845 hr of operation during which 285,605 tons of coal were fired.

This checks closely with the industry's general rule of 1 cent a ton of coal maintenance costs.

**Auxiliary Power.** Auxiliary power is particularly low on spreader stokers. Table 23-13 shows power installations in an Iowa central station of 125,000 lb per hr steam capacity to be only 30 hp. As approximately 8 tons of coal are required per hour for this rated capacity, this is 3.75 hp per ton per hr, a low figure. The power for crushing run-of-mine coal to  $-\frac{3}{4}$ -in. mesh is not included, nor are the 75-hp forced-draft fan or the 150-hp induced-draft fan, as these were considered common to all plants of this size and type.

**Water-cooled Walls.** Water-cooled side walls are considered essential, except for small boilers, to prevent high refractory maintenance. It is desirable, however, to use only enough cooling to protect the walls. Too much cooling, especially at the lower combustion rates, may be detrimental to optimum efficiency and interfere with smokeless operation.

<sup>1</sup> BOWMAN, J. W., *Trans. ASME*, vol. 69, No. 3, p. 207, 1947.

**Table 23-13. Typical Auxiliary Power Requirements<sup>1</sup>**  
(Spreader stokers for 125,000-lb steam plant)

	No.	Hp each	Total hp
Spreader units.....	2	1½	3
Traveling grate.....	2	1	2
Overfire air.....	1	10	10
Cinder return.....	1	15	15
Total stoker and firing system ..	..	....	30

NOTE: Crusher to reduce coal to  $\frac{3}{4}$  in. not included. The cinder-return fan is rated 2,100 cfm, 300°F, delivery pressure 15-in. water gauge. The overfire-air fan is rated 3,000 cfm, 70°F, delivery pressure 10-in. water gauge.

<sup>1</sup> DRABELLE, J. M., Burning Low-grade Midwestern Coals on Spreader Stokers with Continuous Ash Discharge, *Trans. ASME*, vol. 69, No. 3, pp. 203-212, April, 1947.

Without water walls, some clinkering difficulties may be encountered, particularly at the higher burning rates and temperatures, and in cases where the ash bed is allowed to build up too thick or to remain on the grate too long. More frequent dumping has solved many such cases, as has air-cooled carborundum brick along the grate line.

**Slag Formation.** There is little tendency toward slag formation on the boiler tubes. Even with furnaces with refractory walls, operated with low excess air and at high capacities and using low-fusion fuels, there may be considerable slagging on the walls but little on the tubes.

**Steam or Air Jets.** In larger boilers and at high burning rates, or where furnace conditions are poor, improvement in smoke emission may be obtained by the use of steam or air jets properly set in the furnace to increase the turbulence materially. A cross fire from jets set at the front corners or four corners of the furnace and aimed somewhat downward toward the rear of the grate is usually quite effective in decreasing smoke.

Steam jets applied in this manner frequently reduce the cinder carry-over by 50 per cent, while the visible smoke is reduced to one-third of its original amount.

The steam consumption of jets will average from 1 to  $1\frac{1}{2}$  per cent of the total steam produced; however, this is usually offset by an improvement in combustion efficiency to leave the reduction in cinder carry-over and smoke as a net gain.

In one example, it was possible to carry about twice the boiler rating, for an increase in heat release of from 20,000 to 40,000 Btu/cu ft/hr, by the use of the jets, with a maximum Ringelmann smoke reading of less than No. 1.

**Preheated Air.** Aside from the direct material reduction in maintenance costs, a major advantage of the cool grates of the spreader stoker is that preheated air can be used to a marked advantage without complications. Some installations are using as high as 400°F, with 300°F as commonplace. However, judgment should be used where low-fusion coals are to be burned, as too much preheat might result in a "pancake" type of clinker.

### Selection of Fuels for Spreader Stokers

Spreader stokers are ideal for a wide range of coals, especially for the low grades of fuels with high ash and low fusion content. They can handle everything from lignite through semianthracite without question, and even anthracite can be burned satisfactorily, subject to certain qualifications.

Nevertheless, there are still some limitations that affect optimum efficiency and performance. Chief among these are sizing and moisture content.

The coal sizing is of the greatest importance. The stoker will burn fuel ranging from slack all through  $\frac{1}{4}$  in. or even  $\frac{1}{8}$  in., to  $1\frac{1}{4}$ - or  $1\frac{1}{2}$ -in. nut and slack. However, a considerable range in size consist is necessary for proper distribution. With double-screened coals, there is a tendency for much of the coal to fall on only one portion of the grate, since the normal action of the stoker depends largely on the different amounts of centrifugal effect on the larger and smaller pieces. If, on the other hand, the size consist is fairly well distributed between coarse and fine, the burning rate and ash bed will be practically uniform over the entire grate surface.

When the coal is too coarse and too large a proportion is above about  $\frac{1}{4}$  in., the fuel bed may not burn down evenly, with resultant clinker in the areas containing the larger sizes. Similarly, if the lumps falling to the grate are too large they cannot be completely consumed during the short time that they are on the grate. The resultant loss can be averted by holding the maximum screen sizing to  $\frac{3}{4}$  in. or less.

Conversely, the use of excessively small fuels, such as with a large proportion below  $\frac{1}{16}$  in., may produce satisfactory combustion conditions, but the cinder carry-over will be high.

To emphasize the effect of coal sizing, de Lorenzi shows the cinder carry-over at different rates of combustion and with several different fuels (see Fig. 23-9). He states that the combustible matter in the carry-over varies from 20 to 60 per cent and that it is almost directly proportionate to the burning rate. From 25 to 50 per cent of this material will be collected in the boiler passes. By returning these fines to the furnace, approximately 50 per cent of their heat value can be recovered.

In general, high-moisture fuels give less efficient performance than those having lower moisture content because of the more difficult feeding and distributional problems. When the coal is fine and dry, it tends to feed too rapidly; when wet the particles may cohere and stick to the feeder to result in erratic performance. Obviously this would not apply if the moisture was inherent, as is much of that in lignite.

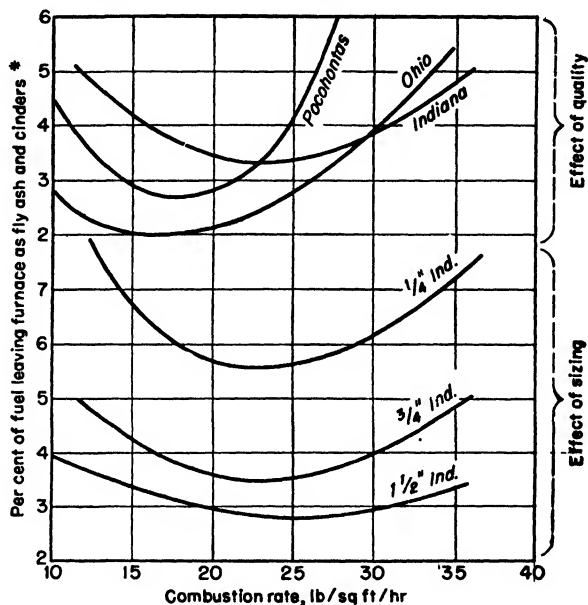


FIG. 23-9. Effect of coal size and quality on cinder carry-over, spreaders. (de Lorenzi, Otto, "Combustion Engineering," Combustion Engineering-Superheater, Inc., New York, 1947, p. 5-8.)

\*Note change in scale.

Caking properties have but little effect upon performance. These properties are greatly reduced by subjecting the fuel to the full effect of the furnace temperature before it reaches the grate. As a result there is a rapid distillation of volatile matter and tarry hydrocarbons, and this almost entirely destroys the tendency to coalesce.

**Operation of Spreader Stokers on Anthracite.** The principal limitation of anthracite for spreader stokers is the fine double screening applied to all mine sizes excepting the lowest or smallest size of a particular breaker. This narrows the size consist with the effect of spotty distribution as was previously described.

Yard screenings have been fired with marked success as have mixtures of anthracite and bituminous coal. While there is no available record of mixtures of anthracite sizes, it is believed that these could be satisfactorily worked out if uniform mixtures could be obtained.

In general, anthracites operate with less attention and more uniform results as the volatile content increases.

With anthracite, somewhat better results have been reported when firing intermittently instead of continuously.

### Typical Operations and Uses

A stoker burning Colorado lignite containing 20 per cent moisture and 9,500 Btu is reported with boiler and economizer efficiencies of 82 per cent. It operated continuously for 6-month periods without shutdowns, and then only for periodic cleanings and inspection.

A plant designed for Indiana coal averaging 10,050 Btu has shown daily efficiencies of 83 per cent with 65 lb/sq ft/hr. Designed for 210,000 lb steam per hr, 225,000 lb have been carried. At a time when the plant had burned 90,000 tons of coal, there

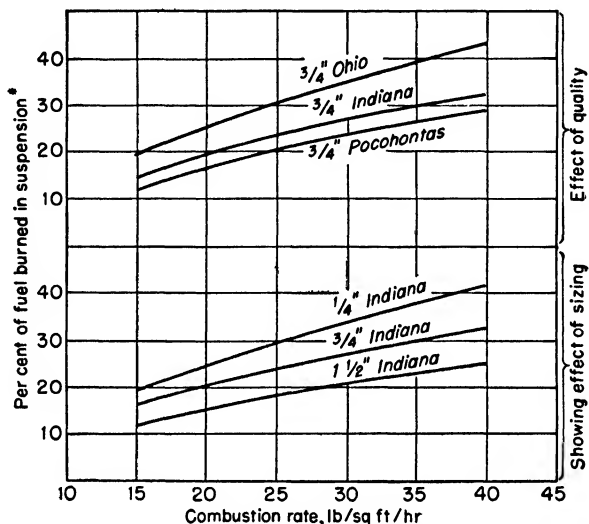


FIG. 23-10. Effect of coal size and quality on amount burned in suspension. (de Lorenzi, Otto, "Combustion Engineering," Combustion Engineering-Superheater, Inc., New York, 1947, p. 5-8.)

\*Note change in scale.

had been no grate replacements nor were the grates showing any signs of growing or overheating.

Table 23-15 shows extensive tests in an Iowa plant. Even though the fuel contained up to 7 per cent sulphur and had an ash-softening temperature as low as 1900°F, the ash was practically free from hard clinkers and the boiler free from slag.

**Marine and Locomotive Use.** In addition to the widespread acceptance of the spreader stoker for general industrial and power use, other uses include marine service, particularly on the Great Lakes; locomotives, where combustion rates are as high as 150 lb sustained and 250 lb for short peaks; at least one mobile plant designed for high-moisture lignite of poor quality; and the conversion of several traveling-grate systems into the continuous-discharge spreader-feed type.

### The British "Sprinkler" Stoker<sup>1</sup>

The British counterpart of the spreader stoker is the "sprinkler" stoker. Two types are available, one with the coal spread by means of a shovel working mechanically and intermittently and having movable grate bars for self-cleaning; and a second

<sup>1</sup> "The Efficient Use of Fuel," pp. 237-240, Chemical Publishing Company, Inc., Brooklyn, 1945.

type with rotary distributor and stationary grate. In the first, coal distribution is obtained by means of cams in the mechanism; in the second, the distribution depends on the angularity of the paddle-type rotors. Both types seem to be used as a replacement for hand-firing, after the fashion of the earlier American spreaders, rather than

**Table 23-14. Typical Test Results with Spreader Stokers with Stationary and Dump Grates<sup>1</sup>**

Test. . . . .	A	B	C	D	E	F	G
Boiler heating surface, sq ft . . . . .	4,970	3,364	7,860	7,350	3,995	4,200	6,180
Economizer . . . . .	Yes	Yes	Yes	Yes	No	No	No
Air heater . . . . .	Yes	Yes	No	No	Yes	No	No
Type of grate . . . . .	Stationary	Stationary	Dump	Dump	Dump	Dump	Dump
Evaporation, from and at 212°F, lb/hr . . . . .	21,200	25,624	97,850	61,839	18,695	29,846	20,822
Carbon dioxide, per cent . . . . .	12 35	12 86	14 30	14 68	14 18	14.60	12.90
Final gas temp, deg F . . . . .	292	297	387	386	326	502	455
Air temp, deg F . . . . .	299	302	82	79	276	74	70
Combustible in refuse, per cent . . . . .	13 0	7 3	11.25	11 31	5 7	2.68	
Coal as fired, Btu/lb . . . . .	14,167	12,165	11,793	11,463	10,756	9,549	7,186
Ash in coal, per cent . . . . .	5 4	12.41	10 76	7 31	11.21	7.35	7.28
Sulphur, per cent . . . . .	0 8	2 19	1 25	1.41	1 55	0.45	0.29
Heat release, Btu/cu ft . . . . .	42,400	47,000	26,400	24,080	16,000	30,500	21,200
Losses:							
Moisture, per cent . . . . .	0 24	0 47	1.07	1.34	1.49	3.08	5.90
Hydrogen, per cent . . . . .	3 78	3 76	3 00	4 83	3.85	4 55	5 27
Dry flue gas, per cent . . . . .	5.22	5 55	7 45	7 04	5 25	10.35	9.91
Combustible in ash, per cent . . . . .	0 79	1.07	0.95	0.72	0.61	0.15	0.54
Radiation and unaccounted, per cent . . . . .	2 47	4 00	2 15	2.13	4 73	4.08	5.20
Heat absorbed (efficiency), per cent . . . . .	87 50	85 14	85 38	83.94	84.07	77.81	73.18

<sup>1</sup> BEERS, R. L., Recent Developments in Spreader Stoker Firing, *Mech. Eng.*, December, 1942, p. 868.

**Table 23-15. Typical Results on Spreader Stokers with Continuous Traveling Grates<sup>1</sup>**

Test . . . . .	1	2	3	4	5	6
Evaporation, from and at 212°F, lb/hr . . . . .	34,648	35,116	44,211	50,370	35,189	46,295
Carbon dioxide, per cent . . . . .	14 3	14 2	13 8	14 8	14 5	14 8
Flue-gas temp, deg F . . . . .	513	521	566	581	520	569
Combustible in refuse, per cent . . . . .	4 68	3 47	4 99	3 01	3 91	4 08
Coal as fired, Btu/lb . . . . .	10,414	9,762	9,917	9,927	10,055	10,179
Ash in coal, per cent . . . . .	14 50	16 59	16 79	16 08	14 80	14 31
Sulphur, per cent . . . . .	6 72	7 20	7.52	5 48	6 48	7 29
Heat release, Btu/cu ft . . . . .	17,650	17,400	23,800	25,400	17,750	23,700
Losses:						
Moisture, per cent . . . . .	1 82	2 28	2 06	2.30	2 02	2.11
Hydrogen, per cent . . . . .	4 54	4 57	4 62	4 73	4 63	4.29
Dry flue gas, per cent . . . . .	9 43	9 80	11 00	10 98	9 72	10 40
Combustible in refuse, per cent . . . . .	0 57	0 37	0 55	0.38	0 52	0 38
Radiation and unaccounted, per cent . . . . .	4 42	2 59	6 50	2 53	3 96	4 81
Heat absorbed (efficiency), per cent . . . . .	79 22	80.39	75 27	79.08	79 15	78 01

<sup>1</sup> BEERS, R. L., Recent Developments in Spreader Stoker Firing, *Mech. Eng.*, December, 1942, p. 868.

for burning any appreciable part of the coal in suspension. A large part of the control and attention recommended is manual. Thin fuel beds, 3 to 5 in., are used. Coals range from ½- to 1½-in. slacks. Ratings of about 30 lb/sq ft/hr are a maximum without serious emission of fines.

Table 23-16. Typical Spreader-stoker Results with Various Fuels<sup>1</sup>

Test series.....	1			2	3			4	5	6
	Data from regular operation			Test	Bureau of Mines tests			Test	Bureau of Mines test	Test
Type of test .....	Very considerable variation			Fairly uniform	Uniform			Fairly uniform	Uniform	Fairly uniform
Type of load. ....	Cross drum, water tube, vertical			4 drum	Cross drum, water tube, vertical			Low head water tube	Cross drum, water tube, horizontal	Cross drum, vertical
Type of boiler and position of baffles. ....	Mixture 35 per cent Anthracite No. 4 No. 3 per cent buckwheat & nut & S bituminous			Bituminous 2-in. N & S	Bituminous 3/4-in. slack			Bituminous 1 1/4-in. slack	Subbituminous R of M	Lignite screenings
Fuel.....	Anthracite No. 2 buckwheat	Anthracite No. 3 buckwheat	Anthracite No. 4 No. 3 per cent buckwheat & nut & S bituminous	Semianthracite 3/8-in. culm	Bituminous 3/4-in. slack <sup>a</sup>	Bituminous 3/4-in. slack	Bituminous 3/4-in. slack	Bituminous 1 1/4-in. slack	Subbituminous R of M	Lignite screenings
Grate surface, sq ft . . . . .	67.5	67.5	67.5	85	52.5	39.0	39.0	90	42.0	25
Heating surface, sq ft . . . . .	2,870	2,870	2,870	12'0"	2,510	2,000	2,000	10'0"	2,040	5'6"
Setting height . . . . .	10'0"	10'0"	10'0"	12'0"	9'6"	9'6"	9'6"	10'0"	11'2"	10'6"
Btu in dry fuel . . . . .	13,670	13,630	13,920	12,250	13,740	13,140	13,260	11,300	12,570	10,680
Heat release, Btu/cu ft/hr . . . . .	39,500	31,300	34,700	15,900	38,600	49,300	81,600	22,800	16,400	16,300
Ringelmann smoke . . . . .	21.7	17.3	18.8	0.8	1.1	1.7	3.6	5.0	1.0	1.3
Coal burned, lb/sq ft/hr . . . . .	7.92	7.93	8.74	21.1	22.0	27.3	44.8	20.4	18.6	19.5
Water evaporation/lb. dry coal . . . . .	60.6	61.3	66.2	6.82	9.04	7.80	7.16	7.92	7.71	70.1
Efficiency, per cent . . . . .				65.1	76.6	68.8	62.6	75.7	73.0	70.1

<sup>1</sup> BARRELY, J. F., The Forced Draft Spreader Stoker, *Trans. ASME*, May, 1937, pp. 259-265.<sup>a</sup> Steam jets used on this test but not on the other three of the series.

TRAVELING-GRATE STOKERS<sup>1</sup>

**Operation.** In both traveling- and chain-grate stokers fuel is fed at the front of a moving flat grate by gravity. The fuel is fed in a layer of uniform thickness under a gate which can be raised or lowered at will, usually by hand, to vary the fuel-bed depth. The moving grate then carries the fresh coal under an ignition arch (usually very short) which serves to distill off the volatiles at a point and in such a manner that they pass over the active fuel bed in their travel through the furnace. Air is supplied under the moving grate in sufficient quantities to complete the burning of the fuel near the end of the travel of the moving grate. Sufficient secondary air to burn the volatiles completely may be introduced over the fuel bed as desired, by various means. The moving grate carries ash over the rear edge to an ashpit or disposal means.

A similar type of grate is used extensively in conjunction with spreader stokers. Moving in the reverse of its customary direction, such a grate receives the larger and unburned particles of incoming coal, where they are held for surface combustion until rejected at the front of the furnace.

Traveling-grate stokers are used with a wide variety of fuels; most particularly with the small sizes of anthracite, coke breeze, and bituminous coals that have characteristics of burning efficiently without being disturbed.

Chain-grate and traveling-grate stokers have the widest application of any equipment for the combustion of solid fuels. All ranks of coal, and coke breeze, can be burned on such equipment with the single exception of caking bituminous coals. They are the ultimate means of burning the No. 3 buckwheat (barley) and No. 4 buckwheat sizes of anthracite.

In principle, both stokers consist of moving grates of the endless-belt type. There are two familiar versions of these, *i.e.*, chain-grate stokers (Babcock & Wilcox, Illinois, Green of Combustion Engineering) and traveling-grate stokers (Coxe of Combustion Engineering, Harrington of Riley, Hazleton). The chain of the chain-grate stoker consists of a broad belt, equal in width to that of the inside of the furnace, made up of individual links several inches in length. The edges of the links are usually serrated to provide free air space for the passage of air for combustion.

The traveling-grate stoker is similar to the chain-grate with the important difference that in traveling grates the actual grate bars consist of small individual castings or "keys" carried forward in endless-belt fashion on chains but, unlike the chain-grate type, not being in themselves a part of the chain.

A characteristic advantage of the traveling-grate stoker is the facility with which burned or broken keys may be replaced without disassembling the chain.

As all other points of construction are generically similar, the remainder of this section applies equally to chain and traveling grates, even though, for the sake of simplicity, the term "traveling grate" is used throughout. In this connection it should be noted that both types are really traveling grates, with the so-called traveling grates having removable links as distinguished from the chain links of the chain-grate type. In order to eliminate the obvious confusion resulting from this similarity, it has been recommended that the more explicit term "bar-and-key grate" be used for the traveling-grate models. However, this suggestion has not as yet been generally adopted by the industry.

Traveling-grate stokers are made in a wide variety of shapes and sizes, in either natural- or forced-draft types, to fill the needs of a wide variety of fuels, furnace constructions, and operational requirements. In addition to being widely used for steaming purposes, they are also a popular source of heat for many special processes and methods.

<sup>1</sup> JOHNSON, ALLEN J., *op. cit.*



In addition to differences in furnace design, as is treated elsewhere, a principal difference between models designed for anthracite and bituminous lies in the free air space through the grate. Keys or links about  $\frac{5}{8}$  in. in width with 4 to 5 per cent are typical of those used for burning No. 3 and No. 4 buckwheat anthracite and river anthracite; while somewhat wider and heavier keys, with 8 to 10 per cent of air space, are better suited for bituminous coals, lignite, and coke breeze.

Natural draft is never employed for anthracite and is optional with bituminous if the ratings and size are within the range that can be obtained without blast pressure.

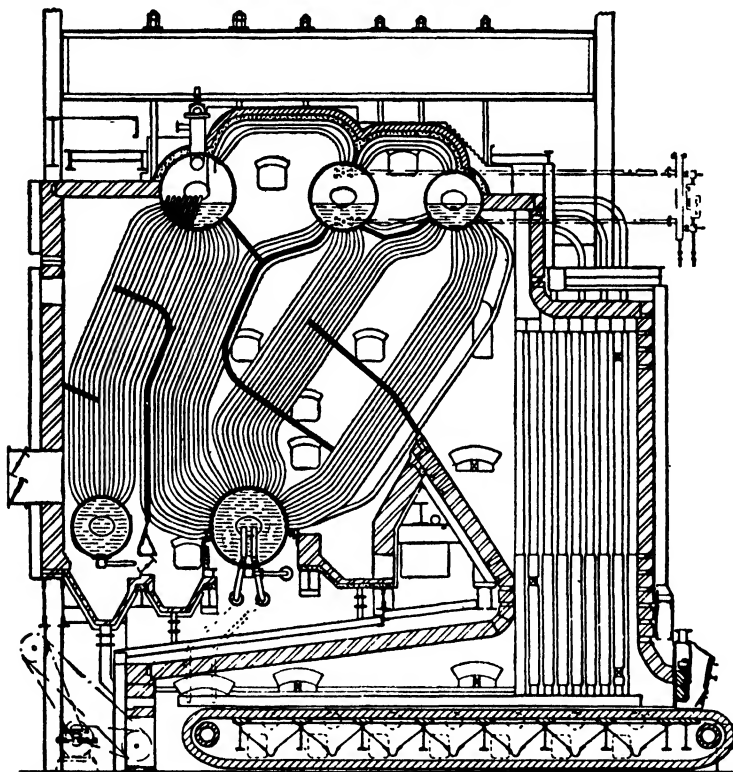


FIG. 23-11. Typical traveling-grate stoker-boiler. *Design data:* Effective grate area 424.5 sq ft, active length 23 ft 7 in., width 18 ft 0 in., rear arch, water-cooled side walls. *Boilers:* 10,500-sq ft Stirlings, 450-lb pressure.

An outstanding advantage of this type of stoker lies in the fact that the air for combustion can be carefully regulated and zoned as combustion proceeds. As the coal burns progressively from its ignition at the front of the grate to ash at the rear, from three to eight or even more wind boxes are employed to divide the air supply into zones for individual control. In extremely large installations, the rear wind box is also subdivided longitudinally to equalize the burning out of the tail end of the fire.

**Sizes Available.** Traveling-grate stokers have been manufactured in sizes ranging from about 15 sq ft to nearly 700 sq ft of grate. The Hazleton and Illinois are well adapted to small installations, with the former listing models as low as 25 hp. Minimum grate widths are about 3 ft as combined with almost any desired length. However, because of the disproportionate per horsepower costs of very small models, due to

the almost fixed base cost of drives, frames, sprockets, and other equipment common to all models, other types of firing usually prove advantageous under about 50 developed hp. At the other extreme, one of the largest traveling-grate stokers so far built is located at the Calco Chemical Co., Bound Brook, N.J. This stoker is 24 ft wide by 28 ft long with 672 sq ft of grate. Another outstanding traveling grate is at the Cedar Street plant of the Pennsylvania Power & Light Co. in Harrisburg, Pa. It is 23 ft wide by 25½ ft long with 586 sq ft of grate.

It has been authoritatively stated that, with barley anthracite of 12,900 Btu, it

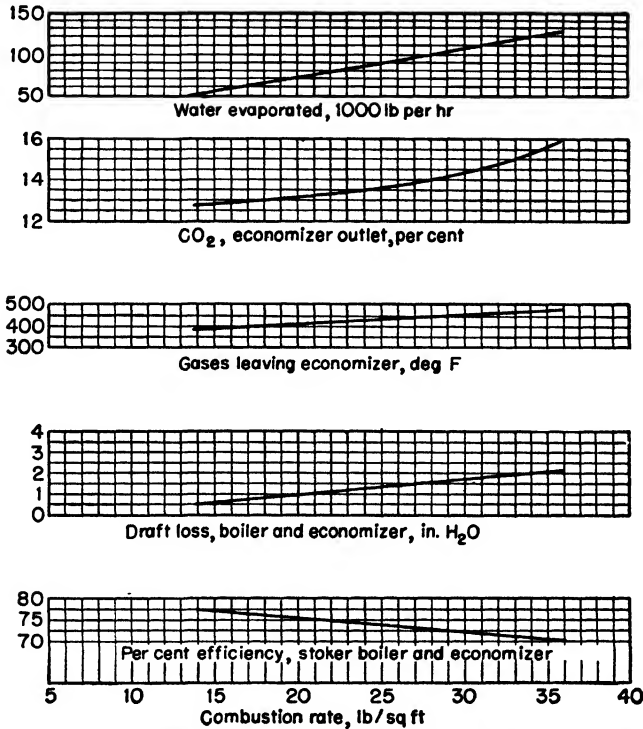


FIG. 23-11a. Operating curves for Stirling boiler traveling grate of Fig. 23-11.

would be possible to design and build a stoker to deliver 300,000 lb steam continuously. This is given as the present practical limit of size for stokers on anthracite.

**Performance Characteristics.** The development of the traveling-grate stoker has seen many changes with material improvements in both flexibility and combustion. Grate speeds, originally 15 fph, now range from 40 fph to as high as 100 fph. Fuel-bed thicknesses have decreased from 6 or 8 in. to a present maximum of 4 or 4½ in. on barley (No. 3 buckwheat) and even thinner on No. 4 buckwheat. Vastly improved arch design has stepped up combustion rates from 25 lb/sq ft/hr to a present practice of 35 to 40 lb anthracite (although the art of traveling-grate furnace design has still not reached the empirical or formula stage that many engineers would like to see). On extremely large jobs where provision for the reuse of flyash and siftings has been made, 45 to 50 lb coal per sq ft per hr have been reported (anthracite).

With the old-type front-arch furnaces, combustible in the ash from barley anthra-

cite of 25 to 30 per cent is considered good practice. With the new-type rear arches, the combustible in the ash should be as low as 10 per cent.  $\text{CO}_2$  of 12 to 14 per cent can be consistently carried without CO.

As to siftings through the grate, Riley states an expectancy of less than  $\frac{1}{4}$  of 1 per cent of the fuel burned even with the fine sizes of anthracite.

**Selection of Anthracite for Traveling-grate Stokers.** The following are the suggestions of George P. Jackson<sup>1</sup> for the selection of anthracite for stokers as operating under various conditions:

1. *Normal Conditions.* From the standpoint of carrying the load efficiency, sizing and moisture are most important. Whether No. 3, No. 4, or other sizes may be the most economical depends on the stoker and furnace arrangement as well as the price of the fuel. With all anthracite, uniformity of size on the grate means a more uniform flow of air through the fuel bed, which is necessary for good combustion and high efficiency. Excessive moisture causes trouble in the mechanical handling of the coal, resulting in bad distribution on the grate and consequent limited efficiency and capacity.

2. *Excessive Load.* Sizing and moisture are even more important at high rating than under normal load conditions. The softening temperature of the ash and its chemical composition are of greater importance at higher ratings because of the higher temperatures in the fuel bed. The presence of an excess of  $\text{Fe}_2\text{O}_3$  in the ash may cause trouble from clinker formation on the grates.

3. *Improper Design of Furnace.* If ignition tends to be unstable, coals of higher volatile content may help. If the settings with a front arch are low, it is quite probable that a fine sizing of coal, such as No. 4 buckwheat, will not give satisfactory results in either efficiency or capacity. Furnace designs should be very carefully studied; and, unless space is very limited, a poor design can often be improved, with a resulting higher efficiency and capacity.

4. *Insufficient Grate to Heat-absorbing Area.* As far as the stoker is concerned with the resulting combustion rates, this item is practically the same as item 2.

5. *Unfavorable Firebrick Conditions.* Impurities in the coal and a low ash-fusion temperature tend toward higher furnace maintenance. Again, an improper design of furnace and improper operation are major factors in furnace maintenance.

6. *Insufficient Draft.* Lack of sufficient draft to provide a slight negative pressure in the furnace will mean high brick maintenance, warped door frames, etc., because the pressure will make the hot furnace gases tend to seep out.

With anthracite and forced draft, lack of the necessary air through the fuel bed may be due to insufficient air pressure from the forced-draft fan. This may result in excessively high fuel-bed and furnace temperatures. Larger sizes of coal as compared with the fine sizes, such as No. 4 buckwheat, would offer a lower resistance to air flow, based on the same thickness of fuel bed. A coal containing ash of higher fusion temperature and of a composition such as to form fewer clinkers would also aid in eliminating trouble from this source. The only real solution to this condition is to make the necessary changes so that sufficient draft will be available to enable the holding of a slight negative pressure in the furnace and so that sufficient air will be obtained through the fuel bed to obtain good combustion and avoid excessive fuel-bed temperatures. This may mean changes in fan equipment, increasing fan speeds, stopping setting leaks, etc.

7. *High Cost of Ash Removal.* The main factor is the amount of refuse to be handled. This is dependent on the percentage of ash in the fuel, together with the

<sup>1</sup> JACKSON, GEORGE P., chief engineer, Combustion Engineering-Superheater, Inc., Consideration in the Selection of Coal for Use in Traveling or Chain-grate Stokers, National Association of Purchasing Agents Bull., 1939.

amount of fly ash to be taken care of, part of which lodges in the boiler setting, and part in the ashpit. Coal low in ash and impurities is desirable from this standpoint. Sizing of coal and design of the furnace will be the determining factors in the carry-over of fly ash. Larger sized coal and a rear arch also reduce the fly ash.

**8. Preheated Air.** Preheated air tends to aid ignition, although the usual reason for its use with stokers is to lower the gas temperature from the boiler exit to increase the efficiency. Maintenance on the stoker grate is only slightly increased where the air temperature is kept below 250°F. Above this point, the maintenance increases more rapidly because of higher metal and fuel-bed temperatures. Fusion temperature of the coal ash is a most important point where preheated air is used, but again, the composition of the ash, especially where iron is contained in the ash in any form, is a factor as well as its fusion temperature.

**Table 23-17. Operating Results on Traveling-grate Stokers with Various Coals<sup>1</sup>**

Type of coal... . . . .	Bituminous Ohio, No. 8	Bituminous Iowa screenings	Anthracite barley	Anthracite No. 4 buckwheat	North Dakota lignite	North Dakota lignite	Coke breeze
Size of boilers, lb/hr . . . .	140,000	80,000	50,000	110,000	130,000	56,000	75,000
Size of stokers . . . . .	15' × 21'	18' × 19'	10' × 17'	19' × 24'	2'9" × 18'	12' × 18'	16' × 18'
Grate area, sq ft . . . . .	315	342	170	456	324	216	288
Ratio grate to lb steam . . . .	445:1	234:1	294:1	241:1	400:1	260:1	260:1
Performance data:							
Lb steam/hr . . . . .	121,000	80,000	50,000	82,500	100,000	56,000	75,000
Efficiency, per cent . . . . .	85 3	83 3	78 5	85.5	80.0	75.5	84.3
CO <sub>2</sub> , per cent. . . . .	14 15	14 2	14.1	14.5	15.0	14.5	15.0
Loss to unburn combustion . . .	1 07	1.5	4.8	5.0	1.0	2.11	3.6
Air pressure stoker zone, in . .	2 3	2.5	3.0	2.6	3.2	3.0	3.0
Coal analysis:							
Btu as fired. . . . .	12,960	9,282	12,215	11,500	6,300	7,194	11,000
Moisture, per cent . . . . .	4 44	15.44	7 4	10 0	39 0	34 52	10 0
Volatile, per cent . . . . .	40 00	32 68	6 3	3 0	27 0	28 80	3 0
Fixed carbon, per cent . . . .	48 00	32 26	75 1	75 0	27 0	29.15	77 0
Ash, per cent . . . . .	7 56	18 62	11.2	12 0	7 0	7.53	10.0
Sulphur, per cent . . . . .	3 19						

<sup>1</sup> Harrington Stoker, Riley Stoker Corp.

**Water-cooled Side Walls.** The trend toward water cooling in boiler furnaces has been increasing during the past 20 years.

In new installations, burning **bituminous** coal, water walls and water-cooled arches, if arches are used, are installed in a large number of boilers. With the modern rear-arch setting, water-cooled walls have been very satisfactory in materially reducing maintenance on the brickwork, and also in reducing temperature of the furnace gases before they enter the boiler tubes. This reduction of temperature tends to reduce the slag formation in the boiler. Some older furnaces have been changed over to partial water cooling with good results; but, where this change is contemplated, considerable thought should be given to its effect on ignition.

Because the ignition is less stable and maintenance is generally lower when burning **anthracite**, water-cooled walls have been installed in comparatively few anthracite-burning furnaces.

**Conversion of Front-arch to Combination-arch Design.** In a number of instances, front-arch settings have been converted to combination arches by the addition of short rear arches. The general result has been to lessen the fly-ash carry-over, reduce the excess air at the rear of the furnace, and improve the efficiency somewhat. A

study must first be made to determine whether the necessary space is available and whether local conditions justify its cost.

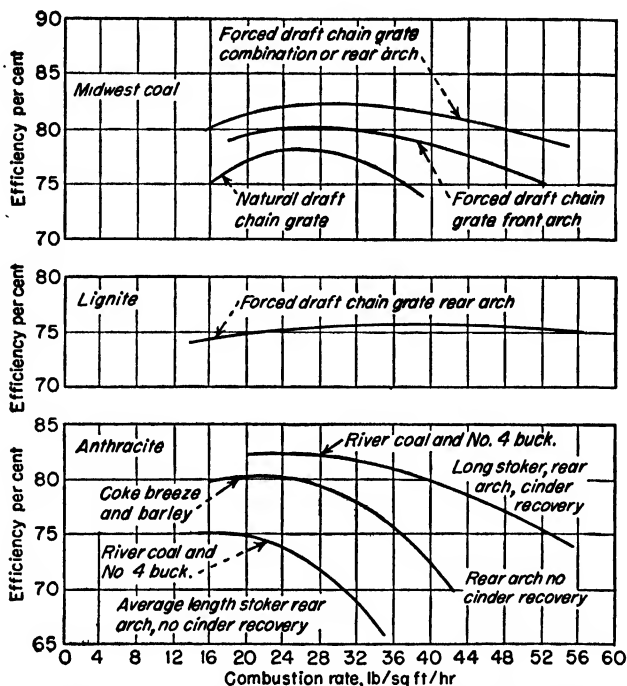


FIG. 23-12. Typical traveling-grate efficiencies with various fuels, based upon a constant exit-gas temperature of 500°F. (de Lorenzi, Otto, "Combustion Engineering," Combustion Engineering-Superheater, Inc., New York, 1947.)

### The Principle of Modulating Automatic Control<sup>1</sup>

The modulating control of stokers has been common practice for many years in large industrial applications where sustained high efficiency and economy of operation are of vital importance. In certain localities, modulated control has become compulsory for all stokers of certain capacities and over. This method of operation and control ensures sustained high efficiencies and elimination of smoke by material improvements in the operating conditions.

A modulating control is an automatic device which operates from steam-pressure changes to cause a regulator or actuator to move in the desired direction to increase or decrease the rate of feed of both fuel and air in small increments. As the load on a boiler increases or decreases, it is reflected in an increase or decrease in boiler pressure. The modulating control then acts to change the coal and air feeds slightly until the heat output from the fuel comes into balance with the boiler load. In addition, furnace temperatures and operation are leveled off at optimum efficiency.

A modulated stoker installation should be equipped with automatic control of the uptake damper, operated from furnace draft changes so as to maintain a predetermined constant rate of furnace draft.

In larger plants more complex systems of control are sometimes employed.

<sup>1</sup> "Smoke," Perfex Corp., Milwaukee, Wis., 1947.

### PULVERIZED-COAL FIRING

Among the more important advantages of firing coal in pulverized form are:

1. Ability to carry higher continuous  $\text{CO}_2$  than many other types of firing. In most cases, this can be accomplished by mere regulation and adjustment.
2. Virtually impossible to make  $\text{CO}$ , even with very high  $\text{CO}_2$  (16 per cent).
3. Utilizes practically all the available furnace volume.
4. Close control over shape and distribution of the flame.
5. Close control over the fire during changes in the load.
6. Low banking losses.
7. More or less uniform temperature distribution throughout the furnace.
8. Ability to handle overloads.
9. Ash cleaning is infrequent and more nearly automatic than in many firing systems.
10. Preheated air can be used more advantageously.
11. Radiation and unaccounted losses are lower because of increased cooled-wall surface.
12. Wider selection of fuel, and easier change from one to another.
13. General saving in labor.
14. Maintenance is usually lower.
15. Larger unit sizes are possible.

### Pulverized-coal Burners

The function of the burner for pulverized coal, according to de Lorenzi,<sup>1</sup> is as follows:

1. Stability of ignition
2. Effective adjustment for control of ignition point and flame shape
3. Completeness of combustion
4. Uniform distribution of excess air and temperature leaving the furnace
5. Freedom from localized slag deposits
6. Protection against overheating, internal fires, and excessive wear in the burner
7. Accessibility for adjustment and maintenance

The **velocity of flame propagation** is directly affected by the ratio of primary air, as indicated in Fig. 23-13. To prevent combustion in the burner and in fuel piping, the velocity of flame propagation must be less than the velocity of the air-fuel mix. If the stream velocity beyond the burner is too great, ignition will occur too far beyond the burner. The burner should be fully adjustable so that the velocity of the air-fuel mix is maintained almost constant over the range of operation. If these conditions are met, ignition will always be stable and the flame will start just beyond the burner nozzle.

The **ratio of primary air** to total air is dependent on such factors as the grindability of the coal and the amount of load. For instance, while the primary air will be 10 per cent for full load, it will be as high as 30 per cent for partial load.

**Completeness of combustion** is a function of:

1. Uniform distribution of fuel and air
2. Turbulence imparted to the fuel and air mixture
3. Quantity of excess air
4. Type of firing employed
5. Fineness of pulverization

The relative loss due to unburned carbon in the refuse as affected by several of these factors is shown in Fig. 23-14 and 23-15.

<sup>1</sup> DE LORENZI, OTTO, *op. cit.*, pp. 8-1-8-25.

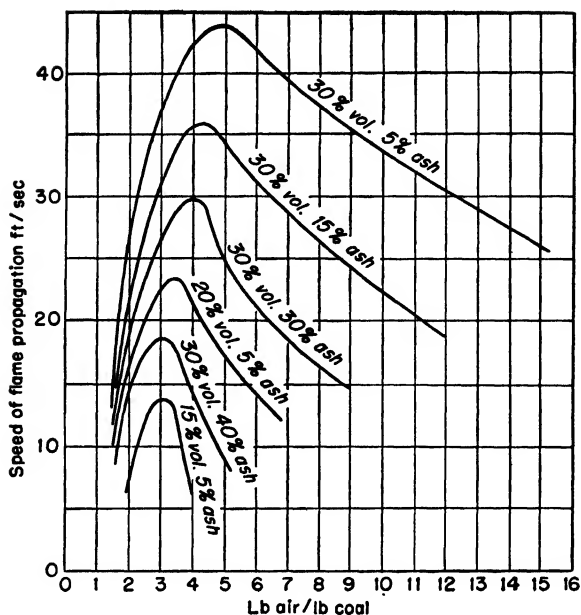


FIG. 23-13. Inflammability curves for mixtures of pulverized coal and air. The air transporting the pulverized coal to the burners is also the burner primary air. This primary air is generally only 10 to 30 per cent of the total air required for combustion. Consequently the air-fuel values of the curve are very low. (de Lorenzi, Otto, "Combustion Engineering," 1st ed., Combustion Engineering-Superheater, Inc., New York, 1947, p. 8.3.)

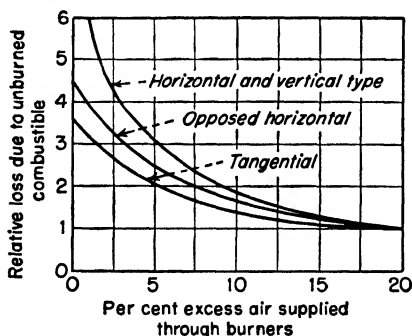


FIG. 23-14. Relation between combustible loss and excess air as influenced by turbulence. (de Lorenzi, Otto, "Combustion Engineering," 1st ed., Combustion Engineering-Superheater, Inc., New York, 1947, p. 8.4.)

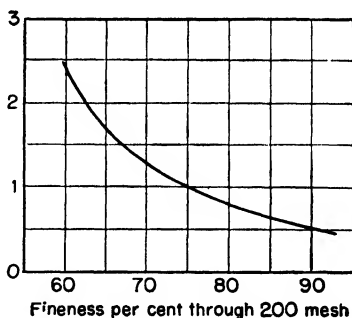


FIG. 23-15. Relation between combustible loss and fineness of pulverization. (de Lorenzi, Otto, "Combustion Engineering," 1st ed., Combustion Engineering-Superheater, Inc., New York, 1947, p. 8.4.)

### Methods of Firing

In general, there are three methods of firing, **vertical**, **horizontal**, and **tangential**. Other types and combinations are modifications of these basic types. Usually, for smaller units, the horizontal circular burner is used, although this type is also used for larger capacities.

Table 23-18. Comparison of Pulverized-coal Burners

Type of firing	Type of burner	Coal volatility	Oil or gas combustion	Furnace flame turbulence produced	General: flame shape, temp, etc.	Furnace shape, usual application	Max furnace heat liberation, Btu/hr/cu ft	
							Natural draft	Forced draft
Vertical	Fan-tail Intertube	Low, medium, high	Not readily adapted	Low	Relatively uniform furnace temp, long flame Uniform high temp in slag- tap furnace, varying in dry ash, decreasing at ash hopper	High and narrow  High for furnaces having dry-ash removal, low for furnaces with molten-ash removal	8,000-16,000	25,000
							Not used for natural draft	15,000-35,000. This figure is subject to considerable variation, depending on coal, load factor, arrange- ment of heat-absorbing surfaces, and size
Hori- zontal	Flare or cir- cular	Low, medium, high	Readily adapted	High	Inherently short flame burner. Flame shape ad- justable. May be located to provide high temp zones as in slag tap, or low temp zones for dry ash	Hopper bottom. Rake- out ash removal. Slag tap	10,000	12,000-35,000
							Not used for natural draft	15,000-35,000. This fig- ure is subject to consider- able variation, depending on coal, load factor, ar- rangement of heat-ab- sorbing surface, and size
Tangen- tial	Tangential	Low, medium, high	Readily adapted	High	Turbulent zone may be selectively positioned either automatically or manually	Slag bottom hopper bot- tom	Not used for natural draft	35,000



In **vertical firing**, both the **fantail** and the **multiple-intertube burners** are used. The fantail or flat burner consists of a long narrow nozzle through which pass the primary air and fuel. Surrounding the fuel nozzle is a passage through which the tertiary air passes. Secondary air is admitted through ports in the furnace wall (see Fig. 23-16).

In **horizontal firing**, both the multiple-intertube burner and the horizontal circular burner are used.

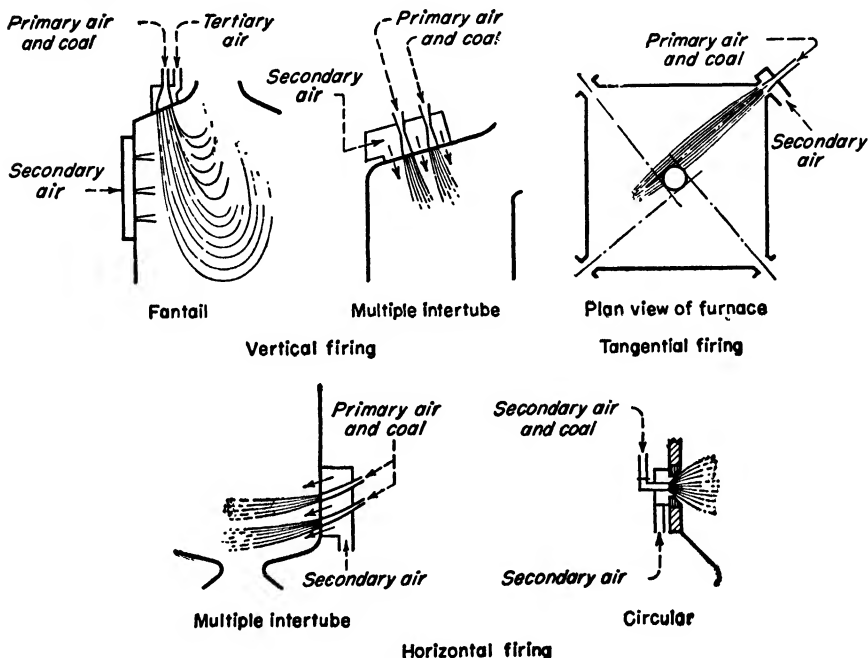


FIG. 23-16. Pulverized coal firing. Diagrammatic sketches of the elements of the burners generally used in medium- and large-sized steam-generating installations.

The multiple-intertube burner (Fig. 23-16) consists of a number of nozzles placed between furnace tubes through which pass the fuel and primary air. Ports placed above and below or to the sides of the nozzles admit secondary air.

The horizontal circular burner has virtually the same components of the oil burner. In fact, these burners are well adapted to the combustion of gas, oil, or coal, singly or in combination, depending on the economics or the availability of the fuel. Coal and primary air are fed through a central nozzle, as indicated in Fig. 23-17. In some designs the inside of the nozzle surface is rifled to give turbulent swirl and good mixing of the primary air and coal. Usually a deflector or impeller is provided at the nozzle tip to help locate and shape the flame. The secondary air enters radially through a set of vanes which gives the stream of air a rotary motion. This spinning air enters the furnace around the nozzle which produces high turbulence and intimate mixing of the coal and air. Adjustment of the secondary-air vanes helps produce changes in the flame shape.

The **horizontal cyclone<sup>1</sup> burner**, illustrated diagrammatically in Fig. 23-18, is designed to burn crushed coal having high-fusion ash. Tests indicate that a rela-

<sup>1</sup> GRUNERT, A. E., L. SKOG, and L. S. WILCOXSON, "The Horizontal Cyclone Burner," annual meeting, ASME, New York, December, 1946.

tively wide range of volatile can be handled, but there is probably a low limit of volatility below which ignition and maintenance of combustion might present difficulties. Ash-fusion temperature should preferably be below 2500°F.

Coal, crushed to pass through 4-mesh size, and air at 450°F are introduced tangentially at 30 to 40 in. water pressure to the cyclone burner. Sufficiently high temperature must be maintained in the burner so that the low-fusion-temperature ash

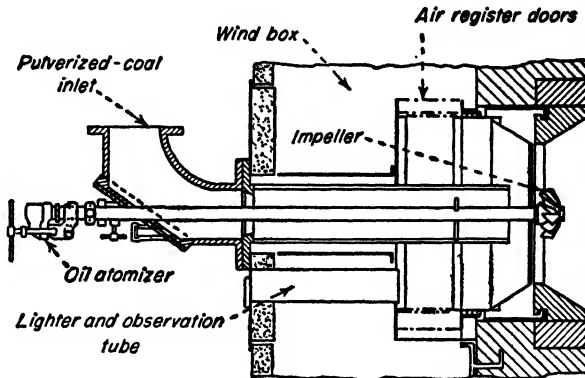


FIG. 23-17. Horizontal circular burner for oil and coal. (The Babcock & Wilcox Co.)

is in a molten state. The whirl in the chamber throws the liquid slag outward so that the inner chamber surface is covered with slag. This covering collects coal and coke, which is swept by high-velocity air, and is burned. The burner is tilted so that molten slag flows down to the continuous slag tap. From tests, it has been found that approximately 80 per cent of the ash is caught as slag in the burner.

In **tangential firing**, as indicated in Fig. 23-16, burners are placed at each corner of the furnace. They are so directed that the center lines of the streams are tangent to

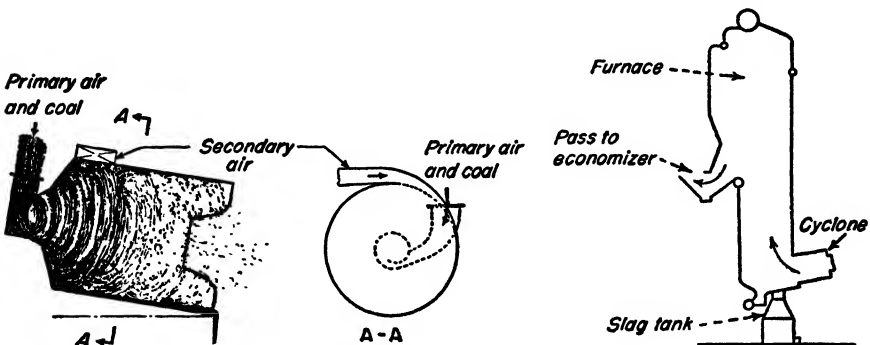


FIG. 23-18. Horizontal cyclone burner.

a small circle at the center of the furnace. These can either be single fuel nozzles or have multiple nozzles placed in a vertical row. Auxiliary air is introduced above and below the fuel nozzles.

For more details on the pulverized-coal burners, consult with Combustion Engineering-Superheaters, Inc., New York; Babcock & Wilcox Co., New York; Peabody Engineering Corp., New York; Riley Stoker Corp., Worcester, Mass.; Erie City Iron Works, Erie, Pa.; and others.

Table 23-19. Performance and Cost Comparisons for Various Types of Coal<sup>1</sup>

Capacity/boiler, lb/hr.....	50,000				100,000				200,000			
	Bituminous		Anthracite		Bituminous	Anthracite		Bituminous	Anthracite		Silt	Nos. 3, 4 buckwheat
			Silt	Nos. 3, 4 buckwheat		Unit pulverized	Stoker		Unit pulverized	Stoker		
Type of coal.....	Unit pulverized	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Stoker
Firing method .....	Unit pulverized	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Unit pulverized	Stoker	Unit pulverized	Stoker
Btu/lb coal, as received . . . . .	13,500	11,500	12,600	12,600	13,500	11,500	12,600	13,500	11,500	12,600	11,500	12,600
Efficiency of boiler, per cent. . . . .	80	77	70	70	80	77	70	80	77	70	77	70
Fuel burned hourly, tons . . . . .	2 5	3 05	3 2	3 2	5 0	6 1	6 3	10 0	12 15	12 7	12 15	12 7
Fuel burned yearly (60 per cent load factor), tons . . . . .	13,125	16,000	16,650	16,650	26,250	32,000	33,000	52,500	64,000	66,600	64,000	66,600
Steam produced/year, million lb . . . . .	262 5	262 5	262 5	262 5	525	525	525	1050	1050	1050	1050	1050
Cost of firing equipment installed . . . . .	\$19,600	\$28,000	\$13,500	\$13,500	\$25,000	\$37,500	\$21,000	\$40,000	\$63,500	\$37,500	\$63,500	\$37,500
Total firing cost per 1,000 lb steam, cents . . . . .	24 5	19 1	23 7	23 7	24 1	18 6	23 6	23 9	18 4	23 5	18 4	23 5

NOTE: Costs are on the basis of 15 per cent fixed charges on firing equipment. Power 33 kw/hr per ton for pulverized anthracite system, 15 kw/hr per ton for pulverized bituminous system. 1 kw/hr per ton for stoker, and fan at 1 cent per kw/hr. Maintenance 4 cents per ton for pulverized anthracite system, 2 cents per ton for pulverized bituminous system, 1 cent per ton for stoker, and 10 cents per ton for stoker arches. Fuel cost \$2.50 per ton of anthracite silt or culm, \$4.50 per ton of bituminous coal, \$3.50 per ton of No. 3 and No. 4 buckwheat mixture; 75 per cent No. 3 and 25 per cent No. 4.

<sup>1</sup> Foster Wheeler Corp.

**Table 23-20. Comparative Operating Cost of Continuous-type Steel-billet-heating Furnace<sup>1</sup>**

(Conditions: Heating value of coal = 14,000 Btu/lb. Heating value of natural gas = 1,050 Btu/cu ft)

Fuel used . . . . .	Natural gas	Pulverized coal
Fuel cost (as of 1944) per million Btu, cents . . .	32 66	20 64
Power cost/kwhr, cents . . .	0 80	0 80
Operating cost/net ton of steel:		
Fuel . . . . .	\$1 672	\$1 030
Power . . . . .	0 039	0 199
Raw-coal conveying. . . . .	. . . .	0 007
Maintenance and supervision . . . . .	. . . .	0 047
Total operating cost/net ton steel . . . . .	\$1 711	\$1.283

<sup>1</sup> At Babcock & Wilcox Tube Co., Beaver Falls, Pa.**Table 23-21. Average Rate of Fuel Consumption by Representative Pulverized-coal-fired Furnaces<sup>1</sup>**

(Conditions: Heating value of coal = 13,500 Btu/lb. Heating value of natural gas = 1,000 Btu/cu ft. Heating value of fuel oil = 149,420 Btu/gal)

Type of furnace	Rate of fuel consumption		
	Pulverized coal, lb/net ton metal	Equivalent ratio	
		Natural gas, cu ft/net ton metal	Fuel oil, gal/net ton metal
Malleable-iron melting furnace <sup>a</sup> . . . . .	760	10,200	68 8
Malleable-iron annealing ovens <sup>b</sup>	500	6,750	45 2
Continuous-type billet-heating furnace <sup>c</sup>	254	3,430	23 0
Cement kilns <sup>c</sup>	128	1,728	11 6
Copper smelting <sup>d</sup>	333 <sup>e</sup>	4,496	30 1

<sup>1</sup> SHERBAN, D. V., Development and Application of Coal-pulverizing and Burning Equipment for Industrial Furnaces and Steam Generation, *Bull.* 3-392, pp. 18-20, Babcock & Wilcox Co., New York (adapted from Federal Power Commission Report of Natural Gas Investigation, Docket G-580).<sup>a</sup> World Power Conference, 1928.<sup>b</sup> American Foundrymen's Association, 1942.<sup>c</sup> Portland Cement Association.<sup>d</sup> Field record.<sup>e</sup> Average per net ton of charge.

### Performance and Operating Costs of Various Fuels

The efficiency of steam-generating units is largely governed by the design of the units to which they are applied. The curves of Fig. 23-19 show spread and variation over capacity range, normally encountered with the principal classes of units to which pulverized coal is applied for steam generation.

Table 23-19, tabulated by Frisch,<sup>1</sup> compares the burning of various types of coal with various types of equipment.

Tables 23-20 and 23-21 show pulverized-coal performances for various industrial furnaces.<sup>2</sup>

<sup>1</sup> FRISCH, MARTIN, Direct Firing of Pulverized Anthracite Silt, *Bull.* BP-41-17, p. 16, Foster Wheeler Corp., New York, 1941.<sup>2</sup> SHERBAN, D. V., Development and Application of Coal-pulverizing and Burning Equipment for Industrial Furnaces and Steam Generation, *Bull.* 3-392, pp. 18-20, Babcock & Wilcox Co., New York (adapted from Federal Power Commission Report of Natural Gas Investigation, Docket G-580).

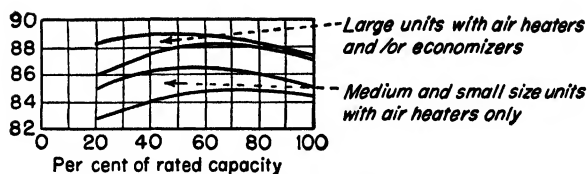


FIG. 23-19. Variation of efficiency vs. capacity range for pulverized coal for steam generation. (de Lorenzi, Otto, "Combustion Engineering, 1st ed., Combustion Engineering—Superheater, Inc., New York, 1947, p. 8.24.)

Table 23-22. Operating Results for Typical Slag-tap Furnaces<sup>1</sup>

Company	Date built	Max steaming rate, lb/hr	Max heat release, Btu/cu ft/hr	Satisfactory tapping cu ft/hr	Fusion point of ash, deg F	Type of furnace	Maintenance cents/ton of coal
Appalachian Electric Power Co . .	1931	355,000	19,950	14,000	2800	Water-cooled	0 5
Buffalo General Electric Co . . .	1931	560,000	35,700	6,900	2100-2500	Water-cooled	0 6
Deepwater Operating Co . . . .	1929	320,000	18,200	18,200	2450	Water-cooled	4.8 <sup>a</sup>
E. I. du Pont de Nemours & Co. . .	1936	75,000	25 300	11,800	2200		
Firestone Tire & Rubber Co . . .	1935	350,000	24,100	10,300	2100-2200	Water-cooled	
Iowa-Nebraska Light & Power Co	1935	160,000	31,750	15,880	2100-2200	Water-cooled	
New York Power & Light Corp . .	1932	350,000	33,400	23,900	2300-2400	Water-cooled	
Northern Indiana Public Service Co . . . . .	1930	345,000	31,800	22,200	2300	Water-cooled	5 6 <sup>b</sup>
Ohio Power Co . . . . .	1931	320,000	29,000	20,000	1900-2100	Water-cooled	2.0
Philadelphia Electric Co . . . . .	1935	600,000	30,000	30,000	2300	Water-cooled	
Potomac Electric Power Co . . . .	1933	375,000	35,000	28,000	2500-2600	Water-cooled	
Public Service Co. of Northern Ill.	1930	300,000	26,500	22,100	2100	Water-cooled	
Public Service Co. of Northern Ill.	1931	500,000	27,200	19,000	2100	Water-cooled	0 9
Sinclair Refining Co., Plant A . . .	1930	120,000	30,000	15,000	2300	Block	2.5
Sinclair Refining Co., Plant B . . .	1931	150,000	32,000	21,300	2400	Block	1 8 coke
Super Power Co. of Illinois . . . .	1930	45,000	27,400	16,800	1950	Water-cooled	2 5

<sup>1</sup> GAUGER, "Symposium on Significance of Tests of Coal," ASTM, 1937.

<sup>a</sup> 4-year average.

<sup>b</sup> Boiler and furnace.

### INCREASING THE STEAM CAPACITY OF EXISTING STOKER INSTALLATIONS

Ollison Craig<sup>1</sup> suggests the following expedients for increasing the steaming capacity of existing stoker and pulverized-coal-fired plants:

In the case of **chain-grate or traveling-grate stokers**, capacity can be increased by increasing the stoker length. This involves increasing the length of the furnace and additional expense for furnace construction.

**Multiple-retort underfeed stokers** can be increased either in width or in length. The width can be increased by adding additional retorts at the sides, involving some furnace reconstruction, except in cases where the removal of corbeling will permit the addition of one or more retorts without disturbing the side walls. In case the stoker length is increased, the furnace will have to be changed.

**Changing from an intermittent-dump arrangement to a continuous ash discharge or clinker grinder** is equivalent to lengthening multiple-retort underfeed stokers, since the area over which coal can be burned as a live fuel bed is increased. The flexibility

<sup>1</sup> CRAIG, OLLISON, Meeting Wartime Fuel Problems, *Mech. Eng.*, vol. 64, No. 10, p. 697, October, 1942.

of operation is also improved because of greater independence of clinkering properties in the fuel.

**Single-retort stokers** cannot be increased much in coal-burning capacity by increasing furnace width, since the installed retort has a fixed width, and no additional retort can be added. Some benefit can be obtained by increasing the length of the side grates, although the effective burning rate over these grates is less than over the retort.

If the single-retort stoker is of the **sectional-retort type**, it then becomes quite simple to increase the length of the stoker by adding a section between the two ends.

**Additional water-cooled boiler surface** improves capacity by increasing the absorption of the boiler and by improving combustion efficiency through the reduction of clinkers (the latter in cases where the additional surface reduces the furnace temperature). Usually the least expensive addition of such water-cooled surface can be had by placing water tubes over the bridge wall. Otherwise it may be necessary to replace the side walls of the furnace with water-tube areas.

**The furnace volume, size, or even shape may be the limiting factor** in a determination of maximum capacity. If so, it will be evidenced by smoke leaving the stack. Usually it is not feasible to increase the size of the furnace, but the lack of size can be compensated for by the use of **overfire air** introduced into the furnace at a short distance above the fuel bed. If this air is properly introduced in a large number of small jets and at sufficient pressure to penetrate the gas streams a sufficient distance, turbulence will occur in such a way as to bring combustible gases into intimate mixture with free oxygen, and combustion of these gases will be completed before entering the tube bank.<sup>1</sup>

Such **overfire air** is of use for underfeed, traveling-grate, and spreader stokers. A fair average requirement for overfire air is 15 per cent of the total air for combustion, this air having a pressure of 10 in. at the nozzles. A separate fan for blowing this air in is desirable. The diversion of air from the forced-draft system is possible but usually proves ineffective because of the lower air pressures.

**Changes may be made in furnace shapes by means of arches** or changes in arches both for purposes of promoting ignition of incoming fuel and for mixing the gases. Properly designed arches produce gas turbulence in the furnace, aid in completing combustion, reduce the necessity for overfire air, and, because combustion is completed in a smaller space, promote increased capacity.

Free-burning Middle Western coal ignites rather easily and is not so dependent upon arch construction for radiation of heat for ignition. More open furnaces can be used, but with open furnaces it is quite essential that overfire air be used for mixing and for turbulence. Eastern coals do not ignite so easily, and more consideration must be given to arch design in order to radiate heat onto the incoming coal.

**Lack of air or lack of draft** frequently restrict capacity. These restrictions may be due to deficiency of forced-draft or induced-draft fans. Capacity frequently can be increased by operating the fans at a higher speed; otherwise larger diameter wheels or even new fans will be necessary.

**Lack of draft capacity**, with positive furnace pressures and resultant higher temperatures and clinker, is **frequently the result of baffle design**. A row of baffle tile can often be removed without affecting the final flue-gas temperature. The areas of passageways between baffles should be carefully studied to make sure there are no restrictions and that the areas decrease in the direction of gas travel, approximately in proportion to the reduction in gas volume.

Other points to check in connection with draft include the sharpness of turns,

<sup>1</sup> See also overfire air under Spreader Stokers.

pressure drops at bends, and the design of the connection between the boiler and the stack.

### INCREASING THE CAPACITY OF EXISTING PULVERIZED-COAL INSTALLATIONS

Many of the older pulverized-coal-fired boilers still have all-refractory furnaces, operate on natural draft, and are subject to restrictions just described for stoker-fired installations. In many of these cases similar remedies apply.

Frequently there are possibilities for very great increases in capacity through the **replacement** of all-refractory furnaces with **water-cooled surfaces**. As such furnaces are usually large, increased heat release seldom causes combustion rates to exceed practical standards.

The **pulverizer** itself may constitute a definite limit to the **capacity** which can be obtained. A pulverizer with just capacity for grinding the requisite coal of 100 grindability will be deficient if required to grind coal having a lower grindability number. **Wet coal** will also reduce the capacity. The latter may involve supplying air to the pulverizer at a higher temperature, supplying hot gas to the pulverizer from the furnace, or even installing a drier.

**Excessive water-cooled surfaces** may have an adverse effect on pulverized-coal capacities. Complete water cooling, to various degrees, causes an increase in unburned carbon, with free-burning Middle Western coals being less affected than Eastern coals. This carbon loss is often tolerated as being a compromise between the minimum-carbon-loss all-refractory furnace of prohibitive first cost. Complete water cooling may also affect stability of ignition and range of load that can be carried. In such cases it may be necessary to apply refractory to the water-cooled walls.

Increased capacity can frequently be obtained by substituting pulverized-coal firing for multiple-retort underfeed stokers. This involves redesign of the furnace, usually accompanied by the addition of some water walls.

#### Increasing Steaming Capacity through a Reduction of Clinker and Slag

The limiting factor in steam output is frequently **ash clinkering** and perhaps **slag**, particularly in boilers designed for other fuels such as oil and converted to either stoker or pulverization. In such cases, E. G. Bailey<sup>1</sup> suggests that increased capacity may be obtained at some sacrifice in efficiency by running with **excess air higher** than normal, at least up to the capacity of the fans and draft equipment.

An alternate method for increasing capacity below the point of clinker or slag is to **cool certain portions of the furnace**, where troublesome slag would form, by introducing flue gases from the boiler outlet. This is more efficient and is usually more economical than is the cooling of a furnace by excess air. It is used in many processes in the petroleum-cracking industry and in superheaters for synthetic rubber, where steam is to be heated to 1400°F.

Troublesome clinkers, caused by high combustion rates, have also been alleviated by water-cooled grates and air-cooled refractory walls, although the results are likely to be less than desired.

One remedy for clinker in a stoker fuel bed is to **provide means whereby the fuel bed can see more water-cooled surface**. More heat will thus be radiated from the fuel bed, with lower bed temperatures permitting higher combustion rates to be carried without troublesome clinker.

One way of exposing more water surface, suggested by Ollison Craig, is to change the shape of the bridge wall so that more of the length of the first row of boiler tubes is exposed (see Fig. 23-20).

In the case of old plants having straight-tube boilers with *C* tile on the bottom row

<sup>1</sup> BAILEY, E. G., Coal Follows Through, *Mech. Eng.*, November, 1942, p. 771.

of tubes, the same effect will be produced if the *C* tile are replaced with *T* tile in the second or third row of tubes. Heat will be radiated to the lower rows of tubes to allow a higher rate of combustion to be carried before clinkering is encountered.

**Temperature Limitations in Special Furnaces.** According to Bailey, metallurgical and ceramic furnaces requiring temperatures below 2000°F may use almost any coal without any slagging difficulty if burned with an oxidizing flame. Temperatures up to 2500 to 2600°F may be attained by selecting coals having ash of very high fusing temperature.

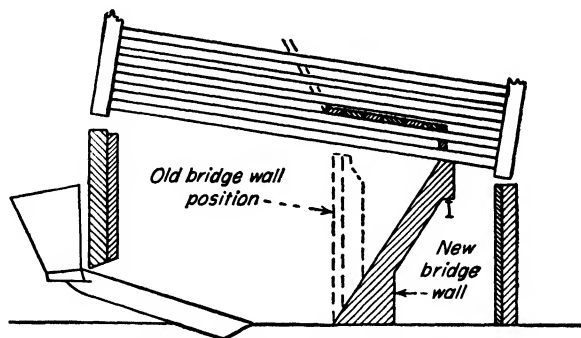


FIG. 23-20. To correct clinkering condition, bridge wall was moved to a position exposing greater length of first row of tubes.

**Slagging in Flat-bottom Pulverized Furnaces.** In older pulverized installations, the furnace bottoms were flat and ash was removed through cleanout doors at the operating-floor level. If required to burn low-fusion coal or to burn more coal, the ash on this bottom fused into a solid mass, because of the short distance from the underside of the flame to the floor. According to Craig, the solution is to move the floor farther from the flame by excavating to a lower level.





## CHAPTER 24

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### FIRING LIQUID AND GASEOUS FUELS

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## FIRING FUEL OIL

### OIL PREPARATION

The equipment necessary for the preparation of fuel oil for combustion is considerably less complicated than that necessary for coal (but more complex than for gas). Bunker C, No. 6 oil, and in some cases No. 5 oil, requires preliminary heating and straining before the pump. Following the pump, additional heating is required to secure the desired viscosity for the burner, along with a final straining (see Fig. 24-10).

#### Oil Heaters

**Types.** The tube-and-shell construction, the general details of which are shown in Fig. 24-1, is the type usually used. Other types also applied to oil-heating appli-

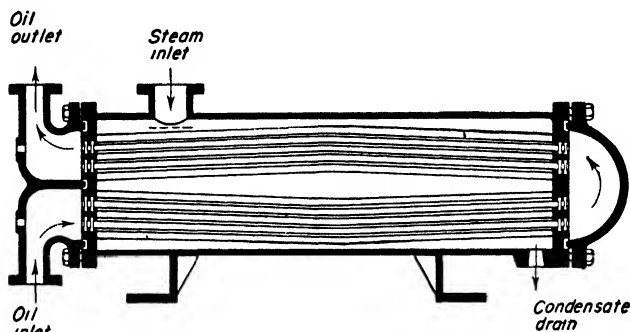


FIG. 24-1. Shell-and-tube heater. (Schutte & Koertling Co.)

cation are the U tube, the coil tube, and the extended surface (fins secured to the tubes) designs.

The **heating fluid** used is generally live steam, although sometimes hot water is used. Whether the steam goes through the tubes or around depends on the designs mentioned.

While the heaters are in operation, care must be exercised to ensure that the heaters are drained to prevent the accumulation of condensate which will blanket the tubes and prevent heat transfer. When the heaters are idle, they must be drained, or corrosion will increase.

Where the condensate is returned to the boiler hot well, precautions must be taken to ensure that oil does not leak into the steam side of the heater and subsequently get into the boiler feed water. (Oil in the boiler brings about the possibility of tube burnout.) To check for oil leakage, fittings can be installed on the heater drain lines, so that samples of the drains can be taken at frequent intervals. Some authorities suggest that, to avoid the danger of oil in the feed water, all the heater drains be sent to waste.

**Viscosity.** In order to have sufficient fluidity to pump to storage or from storage to the final heating, a viscosity of 700 seconds Furol is generally used. If the oil characteristics are not available, a temperature of about 100°F can be used for lack of better information. For mechanical atomization, the viscosity of 150 to 180 seconds Saybolt Universal (temperature about 220°F) depending on the equipment,

is utilized. For steam atomization, the viscosity of 300 to 400 seconds Saybolt (temperature about 185°F) is utilized.

The oil should be heated only to the temperature required for the necessary viscosity. Overheating causes the oil to break down and deposit carbon on the heater surface. This carbon deposit greatly inhibits heat transfer.

**Heat Required.** An approximate expression for the amount of steam required to heat fuel oil is as follows:

$$Q = \frac{3.6 \times G \times (T_o - T_i)}{HA}$$

where  $Q$  = lb steam/hr

$HA$  = heat abstracted from steam, Btu/lb

$G$  = gal oil heated/hr

$T_o$  = temperature of oil at outlet

$T_i$  = temperature of oil at inlet

### Oil Strainers

**Purpose.** In order to eliminate particles of foreign matter from the fuel-oil lines, strainers are employed. A common type of duplex basket strainer is shown in Fig. 24-2.

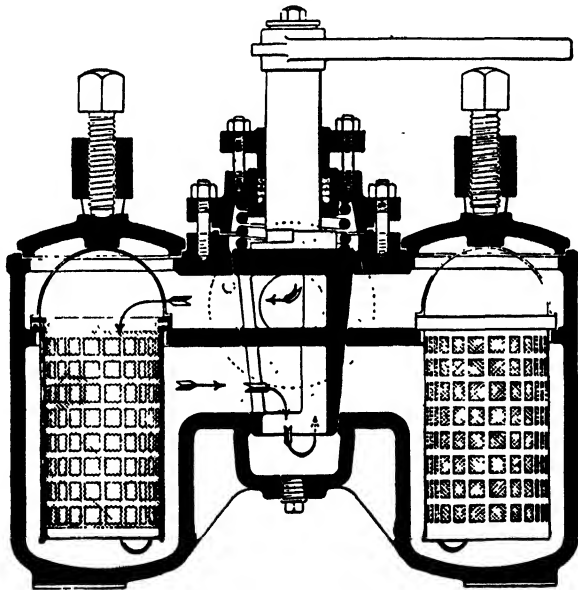


FIG. 24-2. Duplex basket strainer. (Schutte & Koerting Co.)

Strainers should always be installed in duplicate so that one strainer can be cleaned while the other is in operation. The arrangement should be such that the cleaning operation can be accomplished without interrupting service. This can be done with the duplex strainer shown.

**Location.** In order to protect the pump, a coarse strainer of about 8 mesh is installed on the suction of the pump. Having a mesh too fine on the suction is not desirable, since it has a high resistance to the relatively cool oil, sometimes causes loss of suction, and strains the pump.

A finer mesh strainer, about 24 mesh, is installed between the pump and the heater

to remove the finer particles before the fuel oil is delivered to the burning equipment. Sometimes the strainer is located on the discharge of the heater.

### INDUSTRIAL OIL BURNERS

**Oil-burner Function.** It is the function of the burner: (1) to convert the stream of liquid fuel into a finely divided or atomized state and project the fuel oil into the combustion chamber and (2) to have sufficient turbulent mixing to carry away vaporized oil from fuel droplets and supply fresh oxygen to the remaining uncracked or unhydroxylized oil.

**Flame Shape and Characteristics.** In general, there are two flame shapes, the flat flame and the hollow-cone flame. The **flat flame** is seldom used. Since the flame is difficult to penetrate with the requisite amount of air, it is mandatory to bring the air through checkerwork in the furnace floor. This construction permits only one row of burners, and hence the furnace heat output is restricted by its width. Furthermore, when forcing this type of flame, it is difficult to secure penetration of the air to the top of the flame and combustion is incomplete. Use of the flat-flame burners is restricted to units of moderate capacity and small load fluctuations. The **hollow conical flame** is the type in general use. It has the highly desirable characteristics for efficient operation; *i.e.*, it is soft, short, and bushy and hence is readily penetrated by the combustion air. Because of the conical shape, air can penetrate on 360 deg around the cone, whereas the flat flame can secure its air from the bottom side only.

**Atomization.** A number of methods of producing the fine particles of oil are in general use (see Table 24-1).

1. Mechanical atomizer
  - a. Straight pressure type or straight mechanical type
  - b. Straight pressure type having a return flow, or the wide-range atomizer
2. Auxiliary-fluid type
  - a. Steam atomizer
  - b. Air atomizer
3. Rotary-cup atomizer or spinning cup

**Air-mixing Equipment.** The air-mixing equipment consists of, in general, the air register, the diffuser, and the refractory throat. The function of the **air register** is to control the velocity and the direction of the air steam, wrap the air around the flame, help impart a rotation around the longitudinal axis of the flame, and provide turbulent mixing of air and oil. The function of the **diffuser** is to impart a flow of air around the oil particles and also to guide air along the flame. The function of the **refractory throat** is to hold the air around the flame. The mixing of the oil mist and the air is usually accomplished in this throat. Radiation from the refractory throat assists combustion.

**Natural and Forced Draft.** General construction details of the oil nozzle, air register, diffuser, and burner throat do not differ in the forced- and natural-draft application. For mechanical or steam atomization, only the nozzle details differ. However, some of the details of the air register for forced draft might have to be modified because of the mechanical limitations of the wind box surrounding the air register. The advantage of forced-draft operation is the control of a wider air-range variation. The pressure range of natural draft is a matter of only tenths of inches of water; the pressure range of forced draft is a matter of inches of water. Forced-draft operation also offers the advantage of using preheated air. Use of preheated air promotes better combustion.

### Atomization—Mechanical Atomizers

**Straight Pressure Type.** In this type, all the oil entering the nozzle is sprayed into the furnace. Illustrated in Fig. 24-3 is a straight pressure mechanical fuel atomizer.

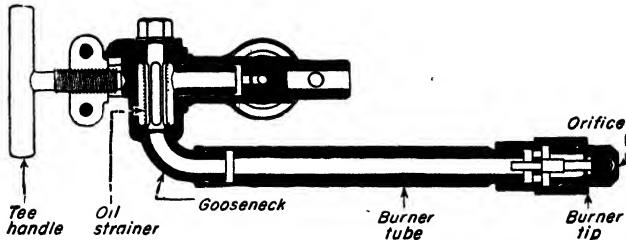


FIG. 24-3. Straight-pressure-type mechanical atomizer. Under suitable pressure and temperature the fuel oil is forced through the orifice in mist form. All of the oil going to the tip passes to the furnace. (Schutte & Koerting Co.)

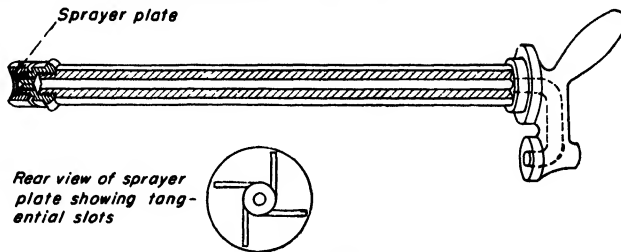


FIG. 24-4. Straight pressure mechanical atomizer. Oil in passing through sprayer-plate tangential grooves is given rotary motion before it passes out through orifice in the form of spray. (Todd Shipyards Corp.)

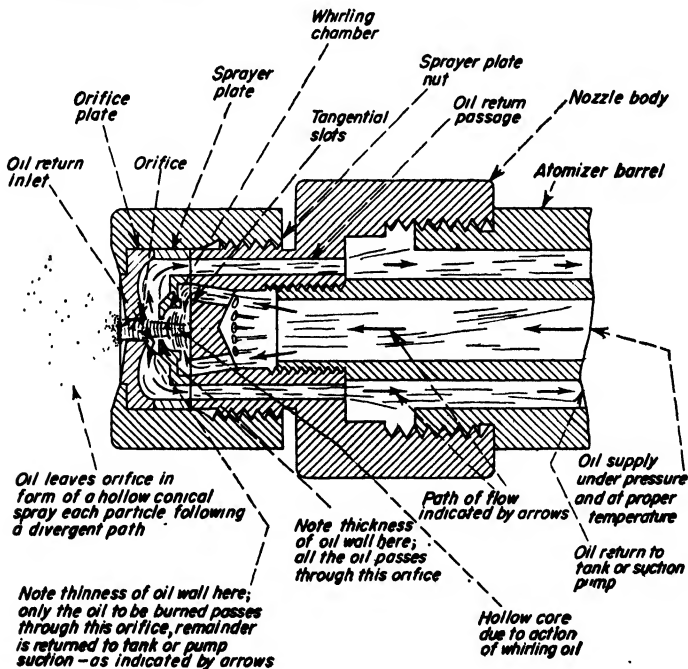


FIG. 24-5. Mechanical atomizer, return-flow type. Oil forced through the center tube passes into the whirling chamber. According to the demand, the oil is proportioned by the return pressure. Some of the oil passes through the orifice, and the remainder goes back through the return-oil passage. (Todd Shipyards Corp.)

The burner nozzle attached to the burner tube consists of three parts, body, tip, and spiral. The fine-pitch spiral gives the oil a rotating motion which causes it to discharge in a finely atomized cone-shaped spray, which promotes efficient combustion when mixed with the proper amount of air. The burner is locked securely into the holder socket when the clamp is in the horizontal or service position. In order to remove the burner, the clamp must be swung down to a vertical position below the tube. To do so, the cock wrench must be turned down, cutting off the flow of oil from the supply line to the burner. It is therefore impossible to remove the burner proper without first shutting off the supply oil.

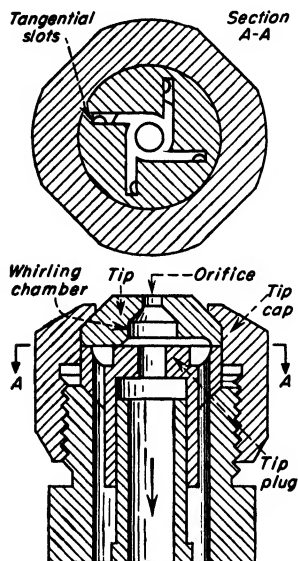


FIG. 24-6. Mechanical atomizer, return-flow type. Oil is fed to the tangential slots through the annular groove, and is given a rotary motion in the whirling chamber due to the tangential slots. Oil required for combustion passes through the orifice, and the remainder is returned (as indicated by the arrow) through the center passage. (Peabody Engineering Corp.)

in the whirling chamber. Under the action of centrifugal force the oil flies outward as it leaves the orifice. Oil not required for combustion demands is returned through the center passage.

**Operational Range—Mechanical Atomizers.** Even with pressure changes of 200 psi the straight pressure burner of Figs. 24-3 and 24-4 has a satisfactory operating range of only  $1\frac{1}{2}$ :1, or at best 2:1. Characteristic curves of this type of burner are shown in Fig. 24-7. Reduction of pressure below 50 psi produces poor atomization and other unsuitable operating characteristics. Consequently the straight pressure type is best suited for relatively constant loads. With decreasing loads, it is necessary to substitute smaller sprayer plates or to cut down on the number of burners in service. Sprayer-plate replacement takes time and interrupts boiler output. When burners are cut in or out of service, poor air distribution results, along with unbalanced use of the furnace volume.

Another type of straight pressure mechanical atomizer is shown in Fig. 24-4. The work of breaking the fuel oil into the form of small particles is accomplished mainly by the sprayer plate. The sprayer plate (Fig. 24-4) consists of a whirl chamber to which the oil passes by way of four nearly tangential slots. Passage of the oil under pressure through these grooves causes the oil to rotate in the central chamber, from which it passes to the orifice, leaving the latter in the form of mist.

**Straight-pressure-type Atomizer—Return Flow.** Illustrated in Fig. 24-5 is a burner of the straight pressure type having a return flow. Oil at proper viscosity and constant pressure is pumped through the central passage where it passes into a whirling chamber from which it passes through the orifice plate. However, only that quantity of atomized oil which is required to satisfy the demand of the load goes into the furnace, the remainder being permitted, by varying the pressure on the return line, to flow back to the return line from the burner.

Another **straight pressure type with return flow** is the burner shown in Fig. 24-6. In this type, oil under pressure is fed to the tangential slots through the annular groove. The pressure drop across the slots is converted into velocity, causing the oil to enter the whirling chamber tangentially at very high speed, thus establishing a rapid rotation of the oil

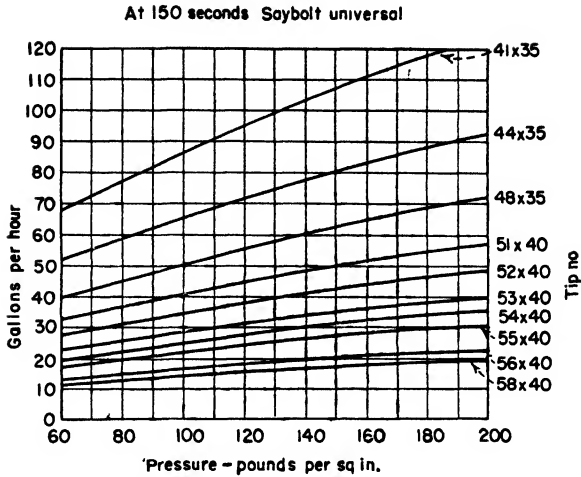


FIG. 24-7. Hourly quantities through "Hex-Press" mechanical burner tips (straight pressure type). Tip nomenclature: the letter *X* indicates a plate with a flat leaving face; the first two digits before the letter indicate the drill size used in making the orifice; the two digits after the letter indicate the ratio of the combined cross-sectional area of the slots to the area of the orifice. (Todd Shipyards Corp.)

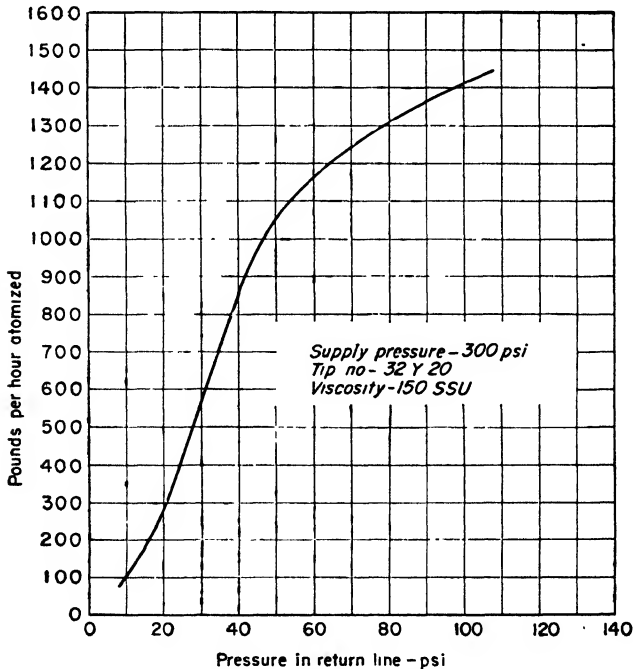


FIG. 24-8. Hourly quantities through "Vec-ee" mechanical tip with return flow. (Todd Shipyards Corp.)



Various methods have been devised to overcome these limitations and increase the usable range of the mechanical atomizing burners. The return-flow nozzle shown in Fig. 24-5 permits wider operational characteristics, as indicated in the characteristic curve of Fig. 24-8.

The nozzle of Fig. 24-6 has its return pressure maintained so that there is a constant differential between the supply and return pressure, as indicated in Fig. 24-9. This is accomplished by means of a spring-loaded diaphragm valve, or a pump, as indicated by Fig. 24-10. Ranges on the constant-differential valve as high as 14:1 have been

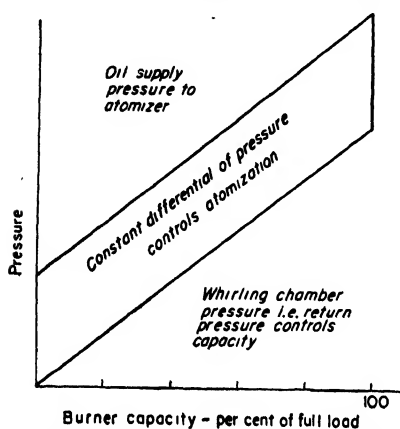


FIG. 24-9. Pressure vs. flow of constant-differential mechanical tip with return flow. The illustration is a generalized representation of pressures in this type system. (Peabody Engineering Corp.)

claimed for actual operation; 10:1 ranges are not uncommon; but in ordinary installations a turndown ratio of 6:1 can be expected, without changing plates or cutting out burners.

#### Atomization—Auxiliary-fluid Type

**Air Atomizer.** In this type, compressed air is the fluid used for the atomization of the oil. Since the cost of compressing the air is comparatively high, there has been little commercial application of the air-atomizing principle.

**Steam Atomizer.** In this type, the atomization of the oil is accomplished by jets of steam. There are two general classifications, the inside mix and the outside mix.

In the inside mix, the atomization by the impingements of the steam jets is carried out inside the nozzle body. The steam further heats the oil, thus reducing

the viscosity. This is the more widely used of the two types.

In the outside mix, the atomization of the oil occurs by the jet impingement outside of the nozzle. This type is now virtually obsolete.

There is some objection to the use of the steam type of atomizer since the steam that is used is lost to the stack and represents just so much more make-up in the feed water. However, as a general rule, the nozzle of the steam-atomizing jets requires less cleaning than that of the mechanical atomizing types.

The steam atomizer gives a finer spray generally than the mechanical type, which allows it to gasify more rapidly. The flame is more resistant to distortion, and hence the diffuser is often omitted. Recently, however, it has been found that the diffuser can give some slight improvement to the combustion efficiency, and it has been incorporated in some designs.

In Fig. 24-11, oil is delivered to the nozzle body, through which it passes into an annular groove in the back of the sprayer plate. From this point, through a series of tangential supply slots, it enters the bowl-shaped whirling chamber at high velocity, rotating therein and following a spiral path in its progress to the outlet orifice where it sprays into the mixing nozzle and is further atomized by steam. The homogeneous mixture of steam and oil then passes through the orifices of the mixing nozzle. The accompanying expansion of the steam atomizes the oil into finely divided particles. Steam consumption claimed is between  $\frac{1}{2}$  per cent to 1 per cent over the entire range of the oil burner.

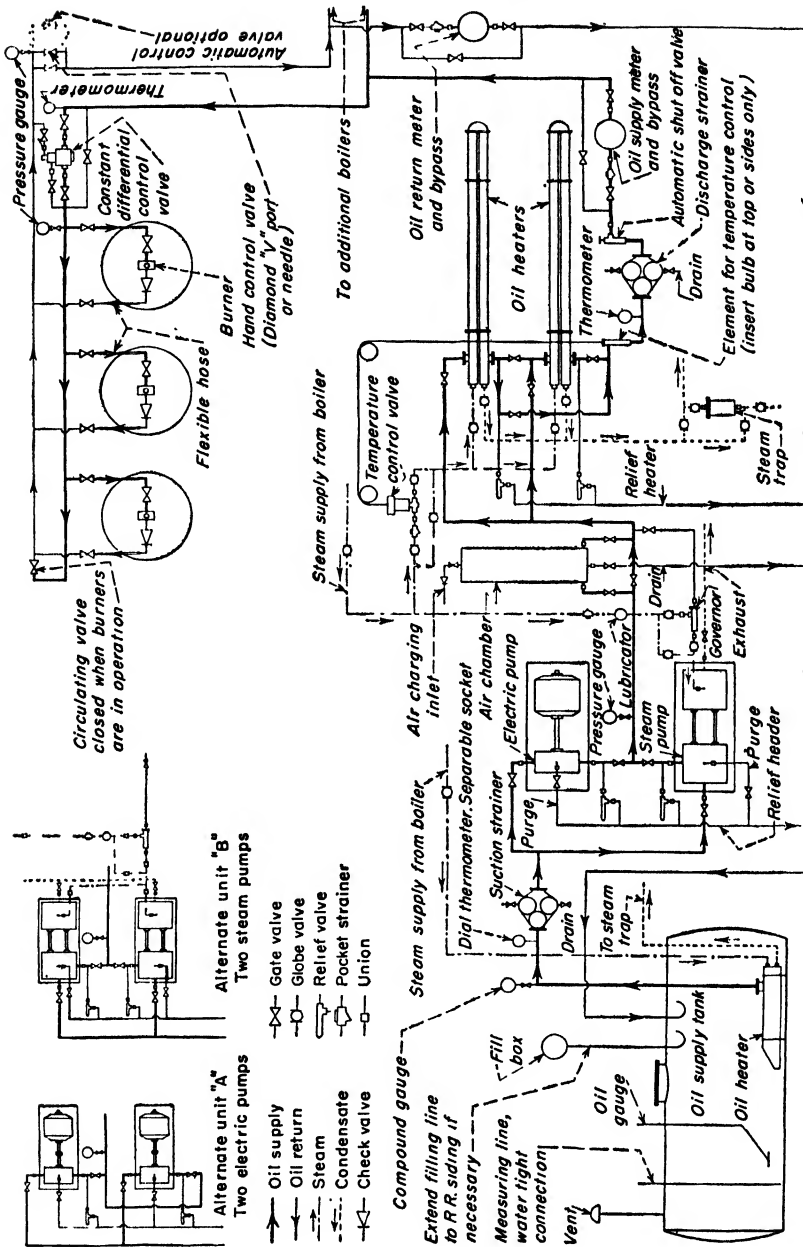


FIG. 24-10. Schematic flow diagram for mechanical system. (Mackenzie Engineering Co.)

In the burner shown as Fig. 24-12, the steam and oil mix in the atomizing venturi and emerge as a hollow cone of mist from the atomizer nozzle.

See Fig. 24-13 for schematic flow diagram for steam-atomizer system.

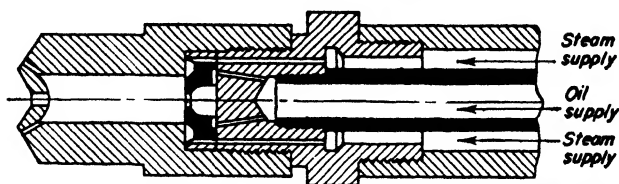


Fig. 24-11. Inside mixing burner, steam atomizing. (Todd Shipyards Corp.)

**Operating Range.** The operating range, usually about 10:1, of the steam-atomizing burner is greater than that of the straight mechanical type, with no change of the burner tip or cutting in or out of the burners. The steam-atomizing burner is therefore more suitable for variable loads.

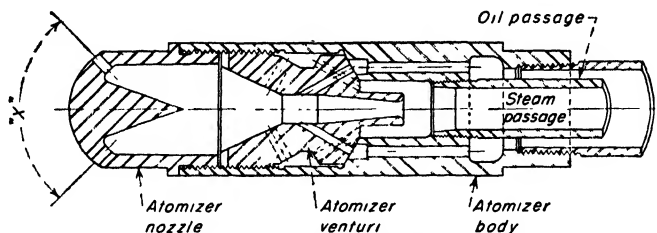


Fig. 24-12. Inside mixing burner, steam atomizing. (The Engineer Company.)

#### Rotary-cup Atomizer

Atomization is accomplished by feeding oil into a hollow cylindrical atomizing cup which is rotated at 3,400 rpm by a directly connected motor in the type shown in Fig. 24-14. The oil flows into and spreads over the inside length of the atomizing cup. On reaching the end of the cup, it is thrown off at right angles to the cup axis as a thin sheet of oil.

Primary air under pressure is supplied by the fan shown and is uniformly directed at this thin sheet of oil, breaking it up into finely atomized particles of oil, the mix then passing into the furnace. Secondary air is supplied by the door underneath or through openings in a checkerwork floor via a special air door, the draft being created by the stack.

The oil supply is No. 5 or No. 6, or lighter at about 300 seconds Saybolt Universal. The operating range is 4:1 or 5:1. Maximum capacity of the largest unit is 1,250 lb of oil per hr.

#### Air-mixing Equipment

The details of construction in general, of the air-mixing equipment do not differ for forced or natural draft or for mechanical or steam atomization.

**Air Register.** The function of the air register is to control the velocity and direction of the air stream, to wrap the air around the flame, and to help impart a rotation around the longitudinal axis of the flame.

In Fig. 24-15 is shown a register applied to natural draft. It consists of a base ring and frustum-shaped cast-iron register body, sliding on four horizontal rods fastened to the base ring and a four-arm spider which supports the burner and hand lever.

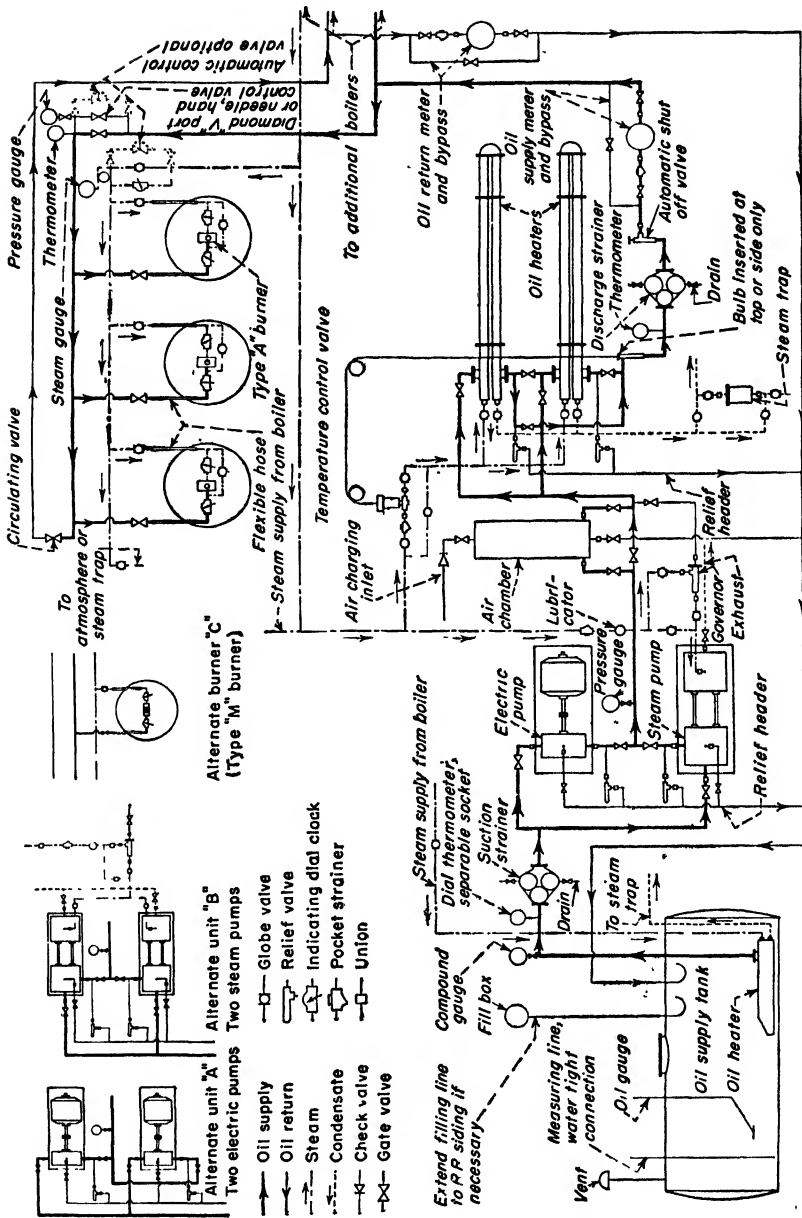


FIG. 24-13. Schematic flow diagram for steam-atomizing system. (Mackenzie Engineering Co.)

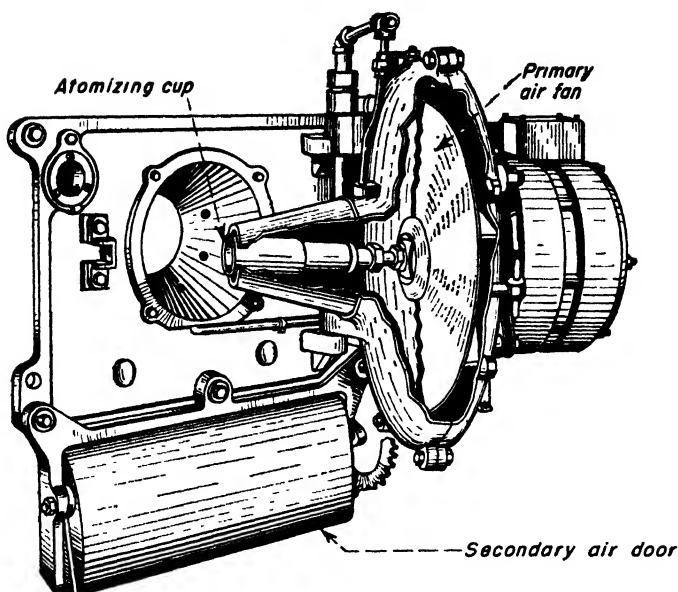


FIG. 24-14. Rotary-cup atomizing burner. Oil is fed to the inside of the atomizing cup which is rotated at 3,400 rpm. This oil is centrifuged from the edge of the cup into the high-velocity air from the primary air fan, which atomizes it and sends it into the furnace. The unit is shown swung out of its operating position. (Todd Shipyards Corp.)

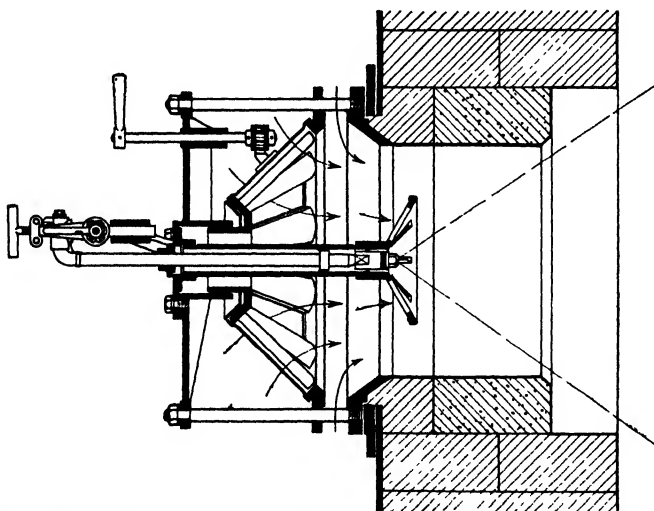


FIG. 24-15. Air-control register. Combustion air is admitted through the rotary shutters of the register. Used for capacities up to 600 lb of oil per hour with furnace drafts of about 0.25 in. of water. Register is shown applied to natural draft conditions. (Schutte & Koerting Co.)

This hand lever is used to operate the air shutter covering the radial openings in the register body.

Eight directional vanes in the form of scoops in Fig. 24-16 guide the major portion of the air to mix with the oil spray after leaving the diffuser and surround the flame after it has passed into the furnace.

The function of the **diffuser** is to impart a flow of air around the oil particles and also to guide air along the flame. The diffuser, types of which are shown in Figs. 24-15 and 24-16, is a hollow metal cone, slotted or pierced with holes. Its shielding action prevents the high-velocity air from blowing the flame from the tip; and, at the same time, the slots or holes allow a limited amount of air to initiate combustion and thereby promote steady ignition. Good operation of the register demands that the

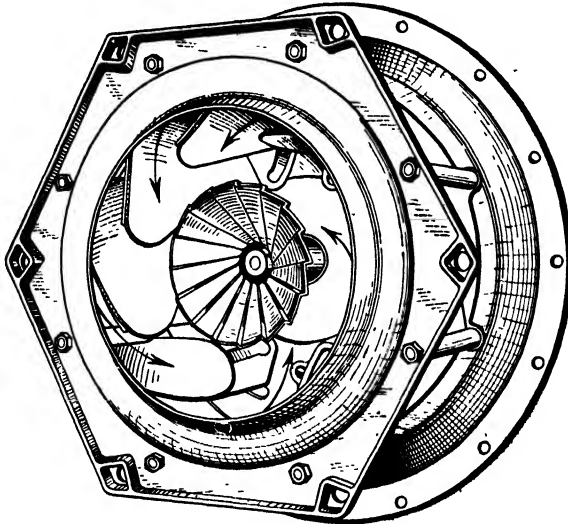


FIG. 24-16. Air-control register. The view of the air register is from the furnace side. The ends of the air-direction vanes as well as the diffuser are clearly shown. (Todd Shipyards Corp.)

diffuser be well back in the throat and that the air from the directional vanes or scoops be wrapped around the flame, yet it should not be so far back in the register that carbon deposits occur on the refractory ring. Diffusers are generally used on mechanical atomizers. They are not usually used on steam atomizers because of jet-aspirating action of the steam which makes them unnecessary. However, some designs recently have incorporated a diffuser because it was found to give some improvement in combustion.

The function of the **refractory throat** is to hold the air closely around the flame. Radiation from the hot refractory assists combustion. The total angle of the conical refractory ring used with the Todd "Hex-Press" burner is 70 deg, and it is important that it should be kept at that figure within close tolerance. Total angles of more than 70 deg with this burner not only tend to allow unnecessary air to pass around the flame but cause reduction of wall thickness at vital points. Too wide refractory angles cause the effect of the air to be lost at short distances from the front wall. Reduction of the angle much below 70 deg will tend to prevent proper expansion of gases from the flame at high rates and to render higher air pressures necessary for smoke prevention. The greatest care should then be taken to secure a total angle of

70 deg with the cone truly circular and concentric with the flame. Egg-shaped or otherwise eccentric openings lead to improper operation and poor results. Condition of refractory rings should be checked frequently, special care being taken that the refractory does not come away from the furnace opening and that no air space is present between the refractory and the front plate.

The throat of the Peabody unit (Fig. 24-17) of venturi design mixes the air and fuel thoroughly with low draft loss. The burner throat is formed from the small tile sections comprising 18 or more segments. These small tile sections allow equal expansion, inhibit spalling, and reduce the danger of cracks developing in the refractory throat, a tendency with large tile segments. Burner-throat tile is secured to the furnace front plate by means of

hook bolts.

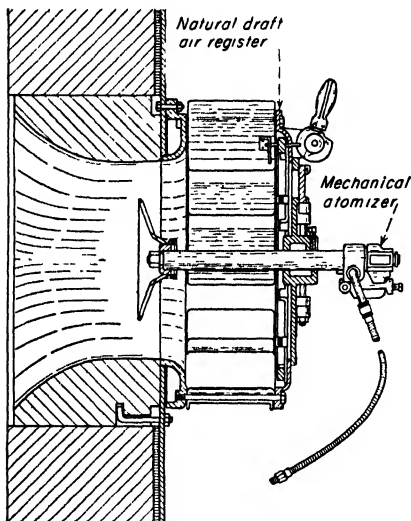


FIG. 24-17. Venturi refractory throat. (Peabody Engineering Corp.)

#### Comparison of Types of Oil Burner According to Type of Atomization<sup>1</sup>

In all oil burners except the mechanical atomizing type, the capacity is usually limited by the volume of the atomizing agent which it is possible to pass through the burner. In other words, it is not generally the size of the oil ports in the burner that governs the capacity but rather the size of the air or steam ports which governs how much air or steam can be passed through the burner and how much air can be induced into the combustion chamber.

In mechanical atomizing burners the capacity is governed by the oil-discharge orifice and the available oil pressure, provided that sufficient air for complete

combustion is available in the combustion chamber.

**Air-atomizing burners** generally produce shorter flames than steam-atomizing burners for equal capacity. The reason is that, in the process of atomization with air, this air which is necessary for combustion comes in immediate contact with the oil particles, allowing ignition to take place more quickly, shortening the flame, and causing the fuel to be consumed more rapidly in a smaller space. With steam atomization, all air for combustion must be mixed with the oil after it is atomized by the steam; consequently, there is a delay in the mixing of the fuel with the air resulting in slower combustion, longer flame, and a limited range of capacity as well as difficulty in maintaining low capacities. This important difference in flame characteristic should not be overlooked in the selection of a burner.

As a specific example, a long narrow combustion chamber, which, while suitable for a conical- or cylindrical-flame steam-atomizing burner, would be improper for a low-pressure air-atomizing burner. The combustion chamber would have to be widened, to assure reasonable service from refractories and good combustion.

**Mechanical atomizing burners** usually develop a shorter bushier flame of low velocity. The angle of flame can be altered to some extent by changing the atomizing nozzle; but, because all the air is provided by secondary means, combustion is not so rapid as with other types of burners, and larger combustion space is usually required.

<sup>1</sup> "Hauck Industrial Combustion Data," pp. 15-16, Hauck Mfg. Co., Brooklyn, N.Y., 1944.

In **rotary-cup burners** the flame characteristics are similar to those in mechanical atomizing burners except that, as a part of the air required for combustion is forced into the combustion chamber around the oil stream, the rate of combustion is increased.

**Applications of Oil-burner Types.** In general, mechanical atomizing and rotary-cup burners are applied on steam-generating and space-heating equipment or equipment requiring large oil-burning capacities, while high-pressure and low-pressure burners are most widely used on heat-treating and other industrial heat-processing applications. Low-pressure air-atomizing burners are most often applied to industrial heating furnaces where multiple burners, ease of automatic control, wide range of control, and low operating cost are important requirements.

#### **Air Required for Atomization in Air-atomizing Burners<sup>1</sup>**

The amount of air required for properly atomizing oil in an air-atomizing burner is affected by several factors such as furnace pressure or draft, air pressure in the burner, grade and temperature of the oil to be burned, maximum temperature to be developed, and the volume of combustion space. Table 24-2 gives the average amount of air required for atomization for both low- and high-pressure deliveries. These figures are subject to variations due to the actual operating conditions of the burner.

Low-pressure air-atomizing burners are usually classed as requiring air at  $\frac{1}{2}$  to 5 lb pressure; high-pressure air-atomizing burners require air at more than 25 lb pressure. Heavy oils require higher pressures than light oils. For example, No. 6 or Bunker C oil should have at least 1 lb and preferably  $1\frac{1}{2}$  lb pressure; while the light oils should have not less than  $\frac{1}{2}$  lb pressure.

#### **Steam Required for High-pressure Steam-atomizing Burners**

These burners require *dry* steam at 30 lb pressure or higher. If steam is wet, the oil will not be properly atomized. The amount of steam required for atomization is variable and depends on the skill and judgment of the burner operator and the furnace conditions. A good operator, under favorable conditions, can atomize a gallon of oil with 2 to 4 lb of steam, while a wasteful operator may use up to 8 lb. For calculations, it is safe to allow 4 lb steam per gal oil, with due allowance for condensation losses in lines leading to the burners.

**Mechanical atomizing burners** atomize oil by forcing it under high pressure to pass through a specially designed fixed orifice which causes the oil to be thrown in a conical spray into the combustion chamber. Air for combustion is forced or drawn in around the spray. They are regarded as one of the cheapest methods of atomizing oil. The oil pressure used is from 75 to 300 lb, depending on the kind of oil and the temperature required. However, this type of burner usually has a limited capacity range, *i.e.*, the burner atomizes efficiently only at its rated capacity with limited turn-down ability. This is due to the fact that, in order to reduce the oil capacity 50 per cent, it is necessary to reduce oil pressure 75 per cent and, at such reduced pressure, the oil ceases to leave the burner orifice at sufficient velocity to be thoroughly atomized.

**Rotary-cup burners** atomize by the action of a high-speed conical metal cup from the outer edge of which the oil is thrown by centrifugal force into a stream of low-pressure air entering the furnace around the cup. The rotary cup is usually attached to an extension of the low-pressure centrifugal blower shaft and the oil is delivered to the cup at low pressure through the shaft or at the side of the cup at its inner edges. The motor, blower, pump, and atomizing cup are usually combined into an integral unit which is attached to the furnace by swing joints to permit swinging the burner away from the furnace for cleaning.

<sup>1</sup> "Hauck Industrial Combustion Data," pp. 14-15, Hauck Mfg. Co., Brooklyn, N.Y., 1944.



Table 24-1. Comparison of Mechanical and Steam Atomization

	Mechanical	Steam
Normal operating range without changing sprayer plates	1½:1, straight pressure. 6:1, with return flow	10:1
Maintenance . . . . .	Frequent cleaning	Infrequent cleaning
Oil viscosity, seconds Saybolt . . . . .	150-180, important	300-400, not so important
Oil pressure for max output, psi . . . . .	200-300	2-150
Steam consumption, per cent. . . . .	Heating and pumping, ½-1 approx	2-5 approx (also some heating and pumping)
Steam loss . . . . .	None, steam is returned to hot well from heater and pump	All the atomizing steam goes up stack
Combustion air pressure . . . . .	Higher	Lower because of steam-jet aspiration
Load type . . . . .	Straight pressure, constant. Return flow, variable	Variable
Maximum capacity, lb/hr . . . . .	6,000	5,000
Starting, cold furnace . . . . .	Smokes badly, but depends on starting rate. Not too smoky if low firing rate used, gradually increasing as furnace heats	Min smoke

Table 24-2. Approximate Amount of Air Required for Atomization<sup>1</sup>

(Showing per cent of total combustion air, i.e., per cent of 1,400 cu ft per gal oil)

Air pressure, psi	With balanced furnace pressure	With moderate furnace draft	Air pressure, psi	With balanced furnace pressure	With moderate furnace draft
Low pressures			High pressures		
½ (8 oz)	66	52	25	15	
¾ (12 oz)	62	47	40	13	
1 (16 oz)	58	42	50	12	
1½ (24 oz)	52	37			
			60	11	
2 (32 oz)	50	33	75	9	
2½ (40 oz)	40	30	100	7	
3 (48 oz)	30	25			

<sup>1</sup> "Hauck Industrial Combustion Data."

Quantity of atomizing agent required per gallon of oil fired is, according to Hauck, as follows:

Low-pressure air burners, cfm . . . . .	10-15
High-pressure air burners, cfm . . . . .	2½- 3
Steam pressure burners, lb steam . . . . .	2- 8
Mechanical atomizing burners . . . . .	None
Rotary-cup burners . . . . .	None

Power required for atomization of 1 gal fuel oil per hr:

Low-pressure air burners, turboblenders, 16 oz, hp . . . . .	0 1
High-pressure air burners, 75 psi, hp . . . . .	0 4
Steam pressure burners, lb steam . . . . .	4 14
Mechanical atomizing burners, hp . . . . .	0.032
Rotary-cup burners, hp . . . . .	0 05

**Cost of Atomization.** On a basis of the above figures and assuming steam costs 50 cents per 1,000 lb and electricity 2 cents per kw-hr, the hourly cost of operation per 100 gal fuel oil burned per hr would be

	Cents/Hr
Mechanical atomization . . . . .	4.8
Low-pressure air turboblender, 16 oz . . . . .	15
Steam atomization . . . . .	20
High-pressure air . . . . .	60

### Oil-burner Control<sup>1</sup>

**Semiautomatic Control.** A semiautomatic oil burner is automatic in the sense that it starts and stops in response to a boiler-pressure switch, operating at a sufficiently high rate of combustion to carry the load by intermittent operation. This causes a cycle of heating and cooling, with considerable fuel loss due to the necessity for reheating the furnace-lining and boiler-heating surfaces after each cutout period.

Installations of this type usually present an aggravated smoke condition for a number of reasons. Such a burner operates at a fixed rate, which may be fairly high, starting up in response to the pressure switch at that fixed rate of feed. Since under any type of draft control other than fully automatic, furnace draft will be high when the burner starts, dense smoke is usually emitted because of the high rate of fuel being fed into a comparatively cold furnace. This condition usually prevails for a number of minutes until the furnace brickwork is brought up to a temperature that will assist and ensure complete combustion.

If no draft-control equipment is used or in the event that a fixed-draft-rate regulator is used, furnace draft increases very materially when there are no gases of combustion to be evacuated. This high rate of draft existing at the moment of starting aggravates the smoke offense because the smoke from the starting puff is drawn rapidly through the boiler.

A semiautomatic oil burner should be converted to fully automatic operation if at all feasible. Smaller plants where such a change-over is not feasible or warranted, can, with little expense, be equipped and adjusted to prevent a considerable portion of the fuel loss and smoke occasioned by start-and-stop operation.

**Draft Control with Start-Stop Operation.** The first step is to adjust the fuel-feeding rate to the load in order to secure as nearly constant operation as possible. Equip the air port with a shutter that is interconnected with the valve controlling the oil feed, and determine the proper arc of operation of the air-port shutter with relation to oil flow by means of gas analyses at several different feeding rates.

**Barometric draft control** should be used if the size of the plant does not warrant fully automatic draft control. If barometric control is used, adjustments should be made at each time that a manual change is made in the oil and air feed, so that the draft conditions will be correct for any given rate of operation and varying volume of gases.

The outstanding advantage of draft control in conjunction with start-and-stop burners is the fact that, during an off period, the furnace draft is maintained at a very low value, thus checking materially, if not stopping, the flow of cold air through the furnace. This serves to increase greatly the length of the off periods and maintain higher temperatures of the boiler surfaces and furnace brickwork.

**Fully automatic draft control** must be of the sequence type, and so adjusted that adequate furnace draft will be established several seconds before the burner starts, in order to prevent puffbacks and fire hazard.

**Fully Automatic Control.** A fully automatic oil-burning installation is one in which the supply of oil and air introduced by the burner, and the quantity of secondary air supplied by natural draft, are closely controlled and automatically regulated in response to slight changes in steam pressure. Such an installation, where properly adjusted and controlled, will operate indefinitely without causing smoke. Its adoption for any oil-burning installation of even nominal size is fully warranted by the substantial savings effected.

A regulating device actuated by steam-pressure changes serves to regulate closely the oil-feed valve, the primary-air intake shutter, and the variable-supply damper in the secondary air port. Such control should properly operate from very slight

<sup>1</sup> "Smoke," p. 10, Perfex Corp., Milwaukee, 1947.

changes in steam pressure, thus avoiding wide "swings" in combustion rate, with their attendant extreme furnace-temperature changes. Control of furnace draft, while a component part of the control set, is usually accomplished by separate and independent means. A separate regulating device positions the uptake or outlet damper to compensate for any slight changes in the rate of draft at the furnace, so that, regardless of the quantity of fuel being fed or the fluctuations in stack draft due to outdoor conditions, the proper rate of draft will prevail at the furnace to supply the correct quantity of secondary air through the variable opening in the secondary air port.

If the rate of furnace draft is maintained at  $\frac{1}{10}$  in. or less, atomization is efficient, and air ports are adequate and proper, smokeless operation results.

#### Firing and Maintaining Oil Burners<sup>1</sup>

**Excess air** wastes more fuel than smoke. Only sufficient air should be used to prevent smoke. If no other means are available to determine the correct amount of air, the simplest way is to reduce the air supply into the furnace to the smoking point, then increase the air supply gradually until the smoke just disappears. This should be repeated every time the fuel-firing rate is changed. Such checks should only be made when the furnace is at normal operating temperatures.

**Draft** should be carried at as low a point as possible. The furnace air-intake doors should be kept open and the damper closed down to reduce air flow into the furnace. This reduces air leakage through cracks or leaks in the boiler setting. Never operate with the fire door open.

**Carbon dioxide** as measured by an Orsat or recorder should be maintained approximately as shown in Table 24-3 for optimum results. Where recorders are used, they should be checked frequently with an Orsat.

**Heating heavy oil** is essential to permit good atomization. The proper heat for various burners and conditions is as shown in Table 24-4. Many difficulties with improper atomization stem from dirty or inadequate oil heaters.

**Excess heating of oil** in storage tanks, whether aboveground or buried, is extremely wasteful. Heavy oil in tanks should thus be heated only sufficiently to permit the pumps to draw the oil, usually 80 to 90°F. Oil vapors coming from heavy-oil tanks indicate a loss of valuable volatile portions of the fuel. The cause should be immediately investigated and corrected.

**Insulation** of all hot-oil lines and containers is important. This should include the fuel-oil heater, manhole pits to buried tanks, and steam and condensate lines to tanks. (See section on Insulation for the correct method of insulating hot lines.)

**Automatic draft regulators** in the flue or breeching should swing freely, respond to slight changes in chimney draft, and be properly adjusted. An automatic draft regulator with corroded pivots is unreliable and should be repaired or replaced.

**Maintenance of Burners.** *Atomizers.* Keep atomizers clean. If of the steam-atomizing type, blow out the burners at each change of shift and whenever the burner is shut down. Replace worn tips; they waste both steam and fuel. Keep atomizing steam dry; wet steam reduces efficiency.

*Rotary Burners.* Clean atomizing cup at regular intervals; a dirty cup makes smoke, soot, and carbon. Atomizing edge of cup must be smooth; if bent, irregular, or cut, replace cup immediately.

*Mechanical Pressure Atomizing Burners.* Change and clean tips frequently. Carbon formation on these tips distorts the spray, causes smoke and soot, and requires wasteful excess air. Examine and replace air diffusers that are warped or have blades

<sup>1</sup> A Guide for Reducing Fuel Consumption in Commercial Plants, U.S. Bur. Mines Bull. 466, p. 24, 1947.

missing. On all grades of oil, examine strainers and filters periodically, and clean or replace when fouled.

**Maintenance of Brickwork.** Air slots in checkerwork must be kept open. Ignition arches and wing walls adjacent to the burner should be periodically inspected and repaired when necessary. Air chamber beneath checkerwork should be kept clean at all times. Burner port tile should be replaced if out of round. Insulation between firebrick combustion chamber and boiler floor means hotter combustion chamber, holds heat longer on shutdown.

**Table 24-3. Recommended CO<sub>2</sub> for Various Classes of Oil Burners<sup>1</sup>**

	Carbon dioxide	
	High rating	Low rating
Commercial and industrial:		
Steam atomizing, manual	13-13½	11
Mechanical, pressure atomizing, manual	12	9
Horizontal rotary, manual	12	9
Horizontal rotary, automatic	11	9
Residential, automatic:		
Pressure gun type	9-11	
Vertical rotary	9-11	
Horizontal rotary	9-11	
Vaporizing	9-11	
Low air pressure	9-11	

<sup>1</sup> U.S. Bur. Mines Bull. 466, p. 24.

**Table 24-4. Recommended Temperatures for Heavy Fuel Oils<sup>1</sup>**

Oil	Burner	Temp, deg F
No. 6 (Bunker C)	Steam-atomizing type	160-180
	Mechanical pressure atomizing	200-250
	Rotary burners, oil heated in suction line	140 min
	Rotary burners, oil heated under pump pressure	180
	Low-pressure-air burners	200
No. 5	Usually burned cold; will atomize and burn better if heated to	110-130
Tank	Just sufficient for pump to handle; avoid overheating	80-90

<sup>1</sup> U.S. Bur. Mines Bull. 466, p. 25, 1947.

## DOMESTIC OIL BURNERS

### Leading Types and Their Characteristics<sup>1</sup>

**Vaporizing-type Burners.** Vaporizing- or pot-type burners are very much in favor for heating units of small size, and for other applications requiring low heat outputs. In a well-designed well-baffled pot burner, a thorough and progressive mixture of air and oil vapor takes place, which can be used with a low, medium, or high setting. The present successful use of the vaporizing-type burner must be credited to a great extent to the improved mechanism for controlling the flow of the oil delivered by gravity to the oil-burning pot; it consists of constant-level and metering valves for high, low, and medium flames. Vaporizing burners are used with either small fans or natural draft. Obviously, with natural draft, there is often difficulty in obtaining proper coordination between oil flow and air supply, especially at periods of low fire and rapid acceleration. Great care must therefore be exercised to avoid abrupt changes of oil flow, either by manual or by automatic control; also to avoid oil flows in excess of that which the maximum input of air to the burner can handle without smoking.

**Low-pressure Atomizing Burners.** In this burner a mixture of primary air and fuel oil is prepared in a "metering pump" and released as a spray through a nozzle, at a pressure that varies from 2 to 7 lb, while secondary air supplied by a fan completes combustion. In this burner, besides the possibility of regulating the burner capacity

<sup>1</sup> BENDER, RENÉ J., "Twenty Years of Progress in Domestic Oil Heating," ASME Paper, Cleveland Semiannual meeting, 1942.

within rather wide limits, the comparatively large oil and air passages made possible by the low-pressure principle permit using a greater variety of fuels with equal success. Likewise, the larger diameter nozzle orifice for any given rate of oil flow adapts them to installations requiring only small flows, as the likelihood of nozzle plugging and irregularities is correspondingly diminished.

**High-pressure Atomizing Burners.** The most popular type of domestic burner, comprising between half and two-thirds of all burners sold, is the high-pressure "gun-type" burner. This burner consists of an oil-pump assembly with oil strainer and pressure-regulating valve, nozzle tube, nozzle tip, air fan, and transformer and electrodes for electric ignition. Unlike the low-pressure gun type, oil capacity cannot be varied, except by changing the nozzle tip. Any change in the atomizing pressure, which is usually most efficient at about 100 psi, changes the quality of the atomization and affects the good operation of the burner.

**Vertical Rotary Burners.** This burner employs an entirely different principle of oil preparation, that of centrifugal atomization by means of a spinning burner rotating inside the combustion chamber around a vertical axis. Fine atomization is obtained by high rotating speeds, often in excess of 10,000 rpm.

While most burners of this type produce a flame shaped like a "sunflower," Timken (Silent Automatic) developed a new principle, called the **wall-wiping flame**. In this unit, fuel oil is conveyed by gravity to a spinning head driven by a vertical electric motor located underneath the hearth. Oil is sprayed by centrifugal force from this spinner and is mixed with air likewise induced from underneath the hearth by means of blades located on the spinner. Installed all around the periphery of the hearth and near the side walls of the boiler or furnace (hence the name of "wall-flame burner") is a ring especially constructed to receive the impact of the air and partly atomized oil mixture. Combustion may be expected to be rather mediocre for a few seconds until the ring becomes heated to a point where it will vaporize the oil and air mixture, transform it into a combustible gas, and cause it to burn upward, very much like a gas flame, with a purple color. High combustion efficiencies can be obtained with this type of burner when properly installed. A potential disadvantage is a tendency to be noisy.

**Horizontal Rotary Burners.** Burners of the horizontal-rotary-cup type are used mostly in larger units, of semi-industrial and industrial sizes, although there has been some application to domestic use, particularly in large homes.

### Improvement through Field Service

Modern oil burners are almost all now designed for and capable of satisfactory efficient service. The greatest drawbacks to the consumers' obtaining satisfactory results in every instance are (1) installation by incompetent or inexperienced parties and (2) a lack of sufficiently frequent field checks for cleaning and adjustment.

**Installation** men should be carefully picked, as all too many have "graduated" the easy way, through desire to sell and service burners instead of knowledge and ability. Among the more important installation details are (1) a proper proportioning of the size of the burner to that of the heating system and (2) a proper and careful design of the oil-burning combustion chamber or furnace. (Burner sizing is discussed below. Data on combustion chambers will be found under Furnace Design.)

**Field Adjustments.** The necessity for frequent cleaning in order to avoid gross wastes of fuel and even more serious difficulties, such as fire and explosions, is well established.

As to combustion adjustments, Bender<sup>1</sup> reports the following as being the "before and after" observations of some 500 installations tested:

<sup>1</sup> "B&W Firebox Handbook," Babcock & Wilcox Co., Refractories Division Bull. R-20B, 1948.

	Avg CO <sub>2</sub>	Avg temp deg F
Conditions as found . . . . .	8 72	553
After readjustments . . . . .	9 16	503

Babcock & Wilcox<sup>1</sup> offers the following suggestions for oil-burner service procedure:

1. **Check the nozzle** for proper flow and spray angle. Be sure all slots are clear. Nozzle capacities change through wear. Always use a pressure gauge for the first tune-up. Usually 80 to 100 psi nozzle pressure gives good results, but do not hesitate to adjust to 130 to 150 lb where necessary for good combustion unless contrary to manufacturer's recommendations.

2. **Check the air delivery** into the flame, as this often has more effect on flame shape than has the nozzle angle. For example, shifting air blades or cones back or forth inside the gun tube may make the flame narrower or wider, cleaner or smokier, or quieter or noisier. To obtain narrow or wide flames from certain burners you may have to obtain special air-handling parts for the gun tubes. The shape of the flame should always fit the combustion chamber.

3. Equip every installation with a good **draft regulator**, and use a draft gauge when setting the regulator. Use the lowest practical firebox draft; from a trace to 0.02 in. is enough for most domestic burners. Use only enough draft to give freedom from smoke, soot, and odors in the basement. Most draft regulators can be set for the lowest draft that they will give.

4. **Examine the flue passages** of the boiler or furnace carefully. Make sure that they are clean and free from obstructions. Look for gas leaks between the sections of rectangular boilers, which permit hot gases to take short cuts to the smoke outlets.

5. Check the possibility of installing **baffles** to reduce stack temperature. Install baffles with a draft gauge and thermometer to avoid furnace back pressures.

6. Carefully **seal all air leaks** permanently, both when the burner is installed and 1 month later. Such leaks can best be found with a candle flame with the burner in full operation and the highest draft.

7. **Adjust the air** carefully to a point just far enough below smoking to avoid complaint. Do not come too close to smoke, but do aim for a rich red flame with optimum CO<sub>2</sub>.

#### Pulsations in Oil-burner Operation<sup>2</sup>

A problem which comes up very frequently during inspections is that of "pulsations," either continuous or occurring only when the burner comes ON or OFF, especially in modern furnace units.

Considerable research work was conducted during 1941 to 1942 in an effort to contribute to this study of pulsation, but at the present writing, only the following negative results can be reported.

1. While it was originally believed that pulsations were caused primarily by an incorrect mixture of the oil spray and the air flow at the burner outlet, experiments have shown that they may occur regardless of how intimately, evenly, and uniformly, the oil and air mixture is produced.

2. Changes in the shape or size of the combustion chamber, or the furnace space immediately above it, do not necessarily eliminate pulsations.

3. Changes in the chimney draft, in either intensity or regularity, do not necessarily eliminate pulsations.

<sup>1</sup> "B&W Firebox Handbook," Babcock & Wilcox Co., Refractories Division Bull. R-20B, 1948.

<sup>2</sup> BENDER, RENÉ J., Twenty Years of Progress in Domestic Oil Heating, *Mech. Eng.*, vol. 64, No. 10, p. 731.

4. Pulsations may be set up in a furnace regardless of the temperature of the furnace, either when the burner starts and stops or during consistent burner operation.

5. It has been demonstrated that the addition to the fuel of an "antiknock" compound such as tetraethyl lead, which makes combustion more uniform in a spark-combustion engine by retarding combustion of the more easily ignitable products, does not eliminate pulsations in an oil furnace.

6. Pulsations will not necessarily stop when the excess air is varied at the burner; neither will increased air pressures at the burner in all cases eliminate pulsations.

7. The shape of the connections between flue pipe and chimney will not cause or stop pulsations.

8. An air vent in the combustion chamber, permitting temporary excess gas pressures to be vented, and allowing secondary air to be admitted, will always stop pulsations, but this expedient usually reduces efficiency and creates a risk of gassy odor.

9. Drawing the air and the products of combustion through the unit by a strong suction at the flue pipe, instead of blowing the air through the burner, will ordinarily eliminate pulsations. A slight drawback is the slight hissing noise of the air. It is felt at the present status of the work that pulsations are not caused by any given condition but by any number of causes, the most likely being the very design of the gas passages through the furnace. If these gas passages could economically be made streamlined, one of the most frequent causes of pulsations would be eliminated. Considerable work is still needed before some satisfactory answer to the pulsation problem in general can be given.

#### Operating Time of Oil Burner vs. Efficiency<sup>1</sup>

According to René J. Bender, fuel oil engineer of the Sinclair Refining Co.:

It would be wrong to assume that the "combustion efficiency" tells the whole story of fuel economy in any given oil-burner installation; the cycle of burner operation is of great importance. By that is meant the percentage of time that the burner is on during any 24-hr period. Oil-burner installations act quite differently when the burner is off; some cool off rapidly; others keep their heat well stored; the quantity of oil that the installation will need to compensate for these losses will vary also. Tests conducted at the Sinclair Refining Co. laboratory prove that it is to advantage to keep the burner on for the longest period of time, for best economy. Tests from which the curve in Fig. 24-18 was plotted led to the following conclusion: If any burner is installed to run constantly during the coldest day of the year, the weather conditions of the Middle West are such that the burner will, as an average, operate 20 to 30 per cent of the time; its efficiency will be nearly 10 per cent below what it would be if operating 100 per cent of the time. In summer, if any burner is equipped to produce hot water, it would be of advantage to reduce the oil flow (oil valve or nozzle) to increase the length of each operating period for better operation (see Fig. 24-18).

#### Methods of Determining Burner Size

The Btu method should be used whenever possible, as it is the most accurate and reliable.

**Btu Method.** To the net Btu load on the boiler or furnace, add from 15 to 50 per cent for piping and pickup allowance (or duct loss and pickup allowance in the case of warm-air heating). This gives the gross Btu load. Divide the gross load by 100,000 (the available Btu per gallon of oil at about 73 per cent efficiency) to find the gallon per hour rate needed.

Modern well-planned warm-air systems with ducts in warm basements need only 15 per cent duct loss and pickup allowance regardless of the size of the heating systems.

Modern hot-water systems with insulated mains need 20 per cent for large systems (net loads higher than about 400,000 Btu) and 30 per cent for the smallest systems.

Steam-heating systems with insulated mains require 30 per cent for large systems and 50 per cent for the smallest systems (net loads below 70,000 Btu per hr).

<sup>1</sup> BENDER, RENÉ J., *loc. cit.*

Firing rates 10 to 25 per cent above normal are needed for (1) extra long ducts or mains, (2) ducts or mains in unheated spaces, (3) poorly insulated steam or water mains, and (4) low boiler or furnace efficiencies.

**Thumb Rules for Burner Size.** The following are approximate thumb rules for figuring burner size and should be used with great discretion:

**1. Steam.** Fire 1 gal for the first 200 sq ft of standing steam radiation, plus an additional  $\frac{1}{3}$  gph for every additional 100 sq ft.

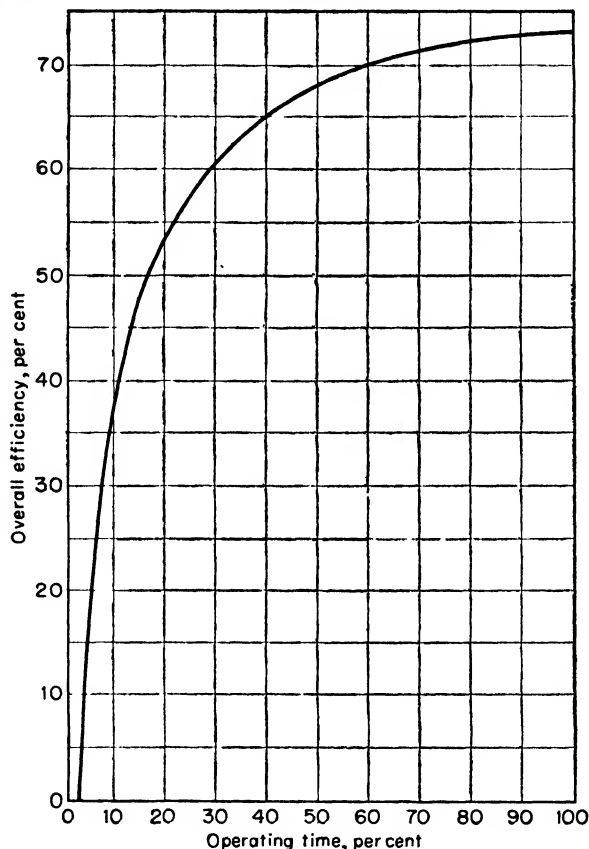


FIG. 24-18. Curve showing boiler efficiency in relation to oil-burner operating time. (Bender, *Mech. Eng.*, October, 1942; *Fuel Oil Engineer*, Sinclair Refining Co.)

**2. Warm Air and Hot Water.** Divide the net Btu load on the furnace or boiler by 75,000 to determine the firing rate.

**3. For Homes Previously Heated by Coal.** Fire 1 gph for the first 8 tons of coal formerly used per year, and  $\frac{1}{10}$  gph additional for each additional ton above 8.

**4. Power Boilers.** Assuming about 65 per cent efficiency. Divide the horsepower desired from the boiler by 3 to determine the gallons per hour oil rate.

**Service Water Heaters.** In using the preceding data, no increase in firing rate is needed where a tank-type indirect water heater is used. However, it is well to increase the firing rate by about  $\frac{1}{3}$  gph where a tankless heater is used. (This applies only to small homes; where the tankless heater is large, a separate additional calculation must be made.)



### Fuel Oil for Domestic-type Burners

A balanced domestic-burner fuel oil, such as the older straight-run types, contains three balanced distillation fractions, light, intermediate, and heavy. The light fraction ignites first and readily and acts as does the kindling in a coal fire to raise the temperature of the intermediate fraction to ignition; the burning of the intermediate then helps further to ignite and burn the heavier final fraction. The entire reaction is started and continued by the readily ignited lower fraction. In thermally cracked oil, for which nearly all domestic-type burners were originally designed, there is a sufficiently large percentage of the lower fraction for easy ignition and combustion with normal air delivery and turbulence; in the catalytic cracked oils there are usually less of the lighter fractions because of the desirability of keeping them in the gasoline. Thus, with the same gravity and other specifications, catalytic cracked oil tends toward more difficult ignition and requires more delicate design and adjustment of the burners to avoid incomplete combustion with the subsequent formation of soot and smoke (unless the latter is "corrected" by the equally objectionable use of wasteful excess air). Manufacturers, cognizant of this difficulty, are rapidly changing the design of their burners to meet the demands of the catalytic oils. An outstanding example is the relatively new "Shell" head which is now being used without royalty by a number of manufacturers.

According to Hulse and Collins,<sup>1</sup> domestic oil burners can be divided into three classes of sensitivity to fuel quality, which is a combination of various properties such as volatility, paraffinicity, carbonizing tendency, and sediment content. In order of increasing sensitivity, these three types are:

1. Pressure-atomizing gun type (high and low pressure)
2. Rotary wall-flame type
3. Vaporizing pot type

All three types are sensitive to sediment which clogs strainers, nozzles, and control valves.

As regards volatility, paraffinicity, and carbonizing tendency, the least sensitive **gun-type** burner gives satisfactory performance on fuels quite deficient in these characteristics. A major fault of many gun-type burners is a sooty period at the start of each cycle; fuels of lower paraffinicity aggravate this condition to some extent.

The **rotary wall-flame** burner is more critical of fuel quality and demands a higher volatility fuel with higher paraffinicity, and lower carbon-forming tendency. This is because of the projection against a cold ring at the start of the burning cycle. A fuel low in diesel index, deficient in volatility, and high in carbon residue will show relatively poor performance in this type of equipment. In some instances shifts to No. 1 fuel oil have been necessary on this account.

The **pot-type** burner is supersensitive to fuel quality and for acceptable performance should be supplied with No. 1 oil or kerosene, unless mechanical draft is used. With current trends toward lower volatility and gravity in No. 2 fuel oils, they will become even less usable in such burners.

**Use of Catalytic Cracked Oils.**<sup>2</sup> While spot conditions may exist that will cause a relatively poor quality component from a certain catalytic-cracking operation to be concentrated in a given batch of heating oil, it cannot be stated that in general poor-quality heating oils are derived from the catalytic-cracking process. Any degradation in burning quality of No. 2 fuel oil which has taken place is properly attributable to the increased production of kerosenes (for pot-type burners), heating oils, and diesel fuels. In this connection, the following points appear worthy of note:

<sup>1</sup> HULSE, STEWART H., and JOHN O. COLLINS, Heating Oil Quality Trends, *Fueloil & Oil Heat*, July, 1948, pp. 63-66.

<sup>2</sup> HULSE, STEWART H., and JOHN O. COLLINS, *op. cit.*

1. In former years, many No. 2 oils contained both kerosene and potential diesel fractions which resulted in high diesel index and a volatility well in excess of the 10 per cent minimum at 440°F prescribed by Commercial Standard specifications. With the large increase in demand for kerosene and diesel fuel, light fractions have not been available as heretofore for blending into heating oil, and consequently there has been a corresponding decrease in volatility and paraffinicity.

2. Contrary to thermal cracking, the fractions in the heavy naphtha range from catalytic cracking have high octane and therefore (except in emergencies) are completely stripped from the heating oil for use in motor gasoline. Consequently, the catalytic heating-oil component is deficient in volatility.

3. In order to make up volume, refineries have included higher boiling components in No. 2 fuel oil.

For all these reasons, heating oils are now being produced of lower volatility than was formerly the case. This trend is illustrated in Table 24-5, which shows the average competitive quality as regards gravity, per cent at 440°F, and diesel index for several years between 1940 and 1947 for No. 2 fuels marketed by eight major oil companies in the Newark, N.J., area.

Since, as has been explained, pot-type and certain rotary-type burners depend upon volatility for proper performance, it is evident that this trend, which shows a drop in both volatility and paraffinicity, has affected performance in certain burners, and not the introduction of catalytic distillates as such. Nevertheless it is significant that all authorities seem agreed that there has been a change in oils and, whether inherently due to the processes in use or to the manipulation of the refining equipment, oil must be selected for specific equipment with increased care.

**Table 24-5. Average Competitive No. 2 Fuel-oil Quality 1940-1947<sup>1</sup>**

	1940	1942	1944	1947
Gravity.....	37.5	35.9	32.6	33.1
Per cent at 440°F..	25.7	15.9	10.5	16.1
Diesel index.....	55.0	52.0	43.5	45.3

<sup>1</sup> HULSE, STEWART H., and JOHN O. COLLINS, Heating Oil Quality Trends, *Fueloil & Oil Heat*, July, 1948.

**Table 24-6. Types of Domestic Oil Burners and Recommended Fuel Oils<sup>1</sup>**

Type	Draft	Grade of fuel oil	Recommended characteristics
Vaporizing:			
Range . . . . .	Natural	Kerosene	Even distillation range. Carbon residue, trace. Good ignition characteristics
Pot. . . . .	Natural	1	Balanced distillation. Low carbon residue. Good ignition characteristics
Vertical rotary vaporizer . . . .	Mechanical	2	Balanced distillation. Low carbon residue. Good ignition characteristics
Atomizing:			
High-pressure mechanical . . . .	Mechanical	2	No sediment. Uniform low viscosity (not more than 45 seconds Saybolt Universal at 100°F). Good ignition characteristics
Low-pressure air . . . . .	Mechanical	2	Low sediment. Not too high viscosity. Good ignition characteristics
Horizontal rotary cup . . . . .	Mechanical	2	Not too high viscosity. Low sediment, max 1% bottom settings and water.

<sup>1</sup> "Oil Heat Guide," p. 10, Shell Oil Co., 1946.

## FIRING GAS BURNERS<sup>1</sup>

If the gas burners are being adjusted by hand the efficiency obtained depends largely upon the fireman. The U.S. Bureau of Mines is authority for the statement

<sup>1</sup> A Guide for Reducing Fuel Consumption in Commercial Plants, *U.S. Bur. Mines Bull* 466, p. 22, 1947.

that as much as 20 per cent of the gas can be saved by efficient firing. If automatic controls are in use, the good fireman will still obtain the higher efficiencies through frequent checks, etc. The following rules are given for the operation of gas burners.

**Flame Characteristics.** Best results are obtained when the flame is slightly blue at the burner tip, gradually changing to a clear light-orange haze, it being clear enough that details on the back wall of the boiler may be readily seen. If the flame is very sharp and of a highly blue color, there is an excess of air with consequent loss of heat. If the flame is lazy and yellow with smoky tips, there is a deficiency of air. In the latter case the furnace draft should be increased by opening the damper or air louvers on burners.

**Carbon Dioxide.** In firing gas in small- and medium-sized boilers, the generally accepted practice is to have a carbon dioxide percentage of 8 to 9 for boilers of the steel-firebox type with very little refractory and 9 to 10 per cent for brick-set boilers such as the horizontal-return-tube (HRT) and water-tube types. The  $\text{CO}_2$  obtainable with perfect combustion of average natural gas is approximately 12 per cent, but attempts to reach this usually result in incomplete combustion with carbon monoxide and soot.

### CLASSIFICATION OF GAS BURNERS<sup>1</sup>

In general, whether the gaseous fuel is manufactured gas, liquefied petroleum gas, or natural gas, the design of burners does not differ in principle. However, changes in such properties as Btu values and gravities do impose a necessity for such a wide range of burner adjustment that a burner, once designed for a particular gas, may be limited in its application.

The numerous types and designs of burner available can usually be classified on a basis of the various permutations and combinations of air pressure and gas pressure employed at the burner. On such a basis, the "torch" type of burner is usually used. However, other basic types are available, usually for specialized applications, such as pipe-type burners, ring burners, surface-combustion burners, and submerged burners. The following outline lists the several types and is followed by brief descriptions of the burner types.

#### I. Open-combustion types

##### A. Torch burners

1. Atmospheric (air at atmospheric pressure)
  - a. Low-pressure gas inspiration (3 to 8 in.)
  - b. High-pressure gas inspiration (4 psi and up)
2. Blast (air above atmospheric, gas at 3 to 8 in.)
3. Low-pressure proportioner (air at 2 psi, gas at 3 to 8 in.  $\text{H}_2\text{O}$ )
4. High-pressure proportioner (air above 5 psi, gas 3 to 8 in.)
5. Total premix
6. Immersion (pipe in fluid)
7. Radiant (pipe in air)

##### B. Pipe burner

1. Atmospheric
2. Blast

##### C. Ring burner (usually atmospheric)

#### II. Surface combustion

#### III. Submerged combustion

### Open-combustion Types

**Torch Burners.** *Atmospheric, Low-pressure Gas.* The air is drawn into the gas stream by the kinetic energy of the gas stream (at pressures from 3 to 8 in. of water)

<sup>1</sup> GOMINGER, B. H., Philadelphia Gas Works, Philadelphia, Pa.

as with a bunsen-type burner, or a venturi-throat injector. Approximately 50 to 70 per cent of the air, or the primary portion, can be induced in this manner. The remaining, or secondary, air is usually drawn in from the atmosphere surrounding the burner nozzle. This last characteristic must not be overlooked in the application of the atmospheric burner.

In general,<sup>1</sup> the burner itself must have the following characteristics:

1. Controllability over a wide range of turndown without danger of flashback or outage. Even for thermostatically controlled operations where the burner is either FULL-ON or OFF, this characteristic is desirable.
2. Uniform distribution of heat, including uniform flame height and good flame distribution over the area being heated.
3. Combustion must be complete. Neither carbon nor carbon monoxide should escape from the flames.
4. The flames must not lift away from the ports.

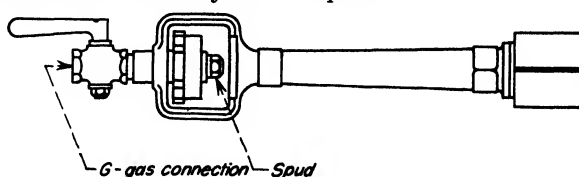


FIG. 24-19. Torch burner, atmospheric. Gas issuing from the spud injects air into the venturi-shaped mixer. (Surface Combustion Corp.)

5. Ignition must take place readily. The flame should travel from port to port over the entire burner rapidly and without difficulty.
6. The burner should operate quietly on ignition, during burning, and on extinction.
7. Substantial and durable construction is essential to withstand severe heating and cooling and remain operative for the life of the appliance in which it is used.

As shown in Fig. 24-19, gas issues from the orifice or spud, injects air into the venturi-shaped mixing chamber, and burns at the tip. This type of burner is made in a wide range of capacities.

Figure 24-20 is an orifice capacity chart for low-pressure gases. The range of pressure used for atmospheric torch burners is within the scope of this chart.

NOTE: Boilers or furnaces employing atmospheric burners should operate at practically no draft to prevent "pulling away" or back "puffs" on the burner. Where chimneys are used, a draft hood to break the draft should be employed.

*Atmospheric, High-pressure Gas Inspiration.* This type of burner is similar to the atmospheric type of burner except that the gas is supplied at a pressure of about 4 psi and upward. Air is injected into the venturi-shaped throat by the kinetic energy of the gas. The energy of the gas must be sufficient to introduce 100 per cent of the air. The gas pressure required is dependent on the thermal characteristics of the gas. According to Surface Combustion, Toledo, Ohio, catalogue BG-44, the pressure of the gas is as follows:

Type of gas	Btu gas/ cu ft	Max pressure, psi
Producer . . .	150	1
Water gas	228	7
Manufactured . .	600	10
Natural. . .	1,000	20-25
Propane . . .	2,500	35 or higher

<sup>1</sup> SHNIDMAN, L., Editor, "Gaseous Fuels," p. 135, AGA, New York, 1948.

The relationship between the spud, the inspirator throat, and the burner tip must be carefully proportioned. A given high-pressure inspirator will not operate properly unless these relationships are correct.

As shown in Fig. 24-21, the only control necessary is the gas valve (1). The gas passes through the spud (3) and into the venturi (6). Air is drawn in through the shutter (4). The mixture of gas and air is piped from the mixer at (7) to the burner or burners.

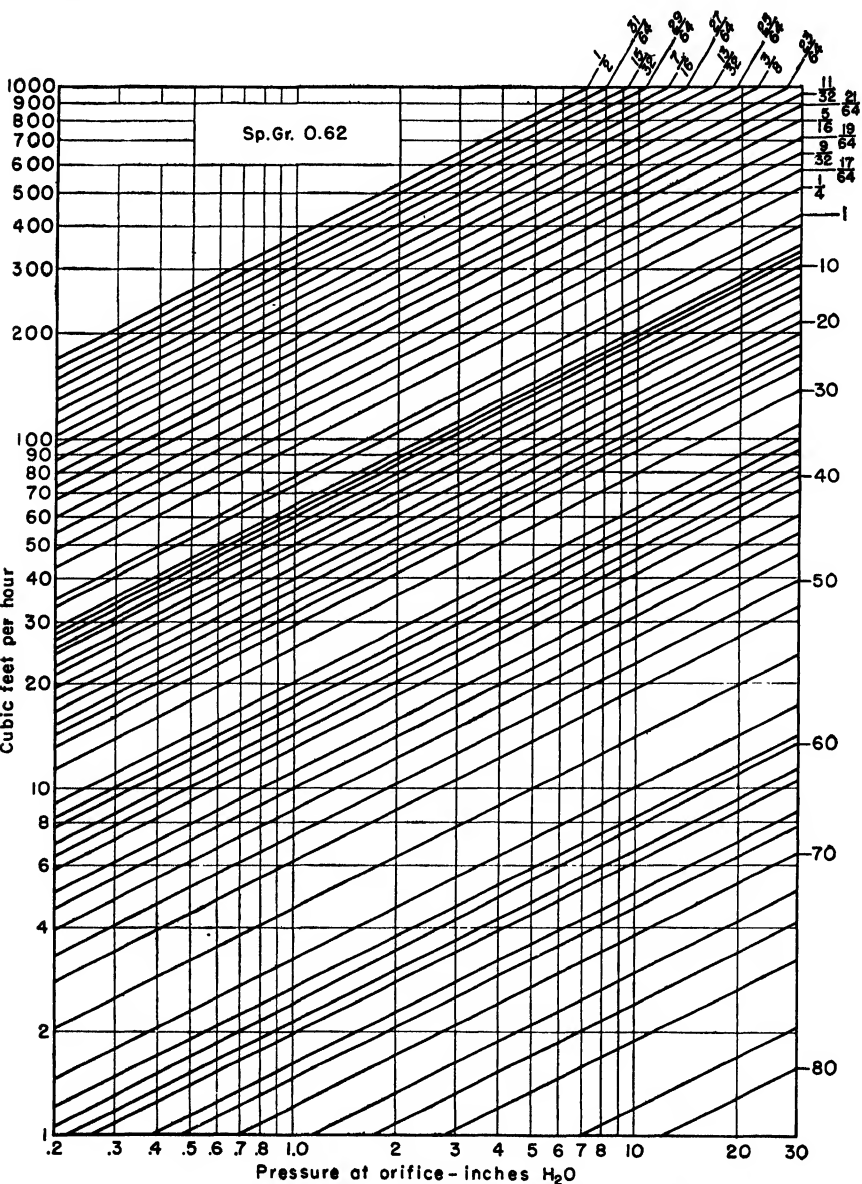


FIG. 24-20. Orifice capacity chart, low-pressure gas. (Surface Combustion Corp.)

**Blast** (air above atmospheric, gas 3 to 8 in.). Where the gas pressure is low, or there is limited combustion space, the blast burner is used. The air is supplied at pressures from 2 to 6 oz per sq in., and the gas at pressures from 3 to 6 in. water. The gas and air are separately proportioned by means of valves. This type has been superseded by the low-pressure proportioner.

**Low-pressure Proportioner** (air at 2 psi, gas at 3 to 8 in.) or *Inspirator*. In order to eliminate the use of two control valves of the blast burners, the low-pressure proportioner was developed. This type utilizes air at 1 to 2 psi and gas at 3 to 8 in. water at the gas governor. The kinetic energy of the air stream is used to inspire, or draw in, the gas held by the gas governor at some low constant pressure, usually zero or atmospheric. Some form of adjustment between the zero regulator and the inspirator chamber is provided, to vary the gas-air mix. Once the adjustment of gas and air is set, it is maintained automatically over the load range.

The proportioner, with its gas governor and mixture adjustment, can be used for 400-Btu gas and up. The proportioning of the burner nozzle, the air jet, and the

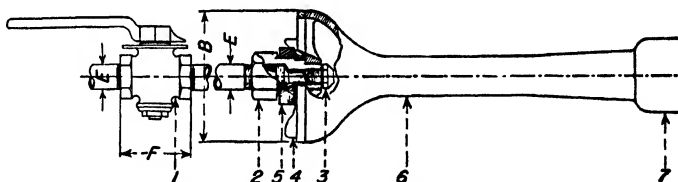


FIG. 24-21. Torch burner, high-pressure gas inspiration. Most of the total air required for combustion is injected into the venturi throat by the kinetic energy of the gas issuing from the spud. (*Hauck Industrial Combustion Data*, p. 71.)

inspirator throat must be maintained within a specified range. Practically any shape of burner nozzle can be supplied through the proportioner. Only one control valve (the air valve) is necessary to change the output. The gas valve is used for turning the gas ON or OFF. Figure 24-22 illustrates a low-pressure proportioner. Air flowing through the insert draws in gas at constant atmospheric (or zero pressure held by the governor) through the orifice. The mixture is piped from the inspirator outlet. Secondary air is needed to complete combustion. This air is supplied from circumambient atmosphere.

To meet the requirements for a furnace of a wide temperature range, the system of Fig. 24-23 is utilized. At lower temperatures an auxiliary supply of air is introduced which gives a large supply of heated gases, promoting quick and uniform heating. At higher temperatures both nozzles function as burners in the usual manner.

**High-pressure Proportioner** (air above 5 psi, gas 3 to 8 in.). The high-pressure proportioner does not differ from the previously described low-pressure proportioner in principle but is designed to operate on the higher pressure air.

**Premix Burners.**<sup>1</sup> Nozzle mixing burners lack the uniform controllability of other types and are not very well suited for producing controlled atmospheres over a wide range of turndown. They tend to make a nonuniform atmosphere because of short time and space for air-gas mixing.

Premixed burners form the largest class of industrial burners and are, in general use, successfully producing all types of atmospheres. It is simply necessary to regulate the air and gas flow to produce the desired condition. Sometimes, where luminosity is desired, these burners are supplemented by a separate supply of unburned gas, or they may be used in combination with carbon-gas burners to pre-

<sup>1</sup> SHENIDMAN, L., *op. cit.*, p. 212.

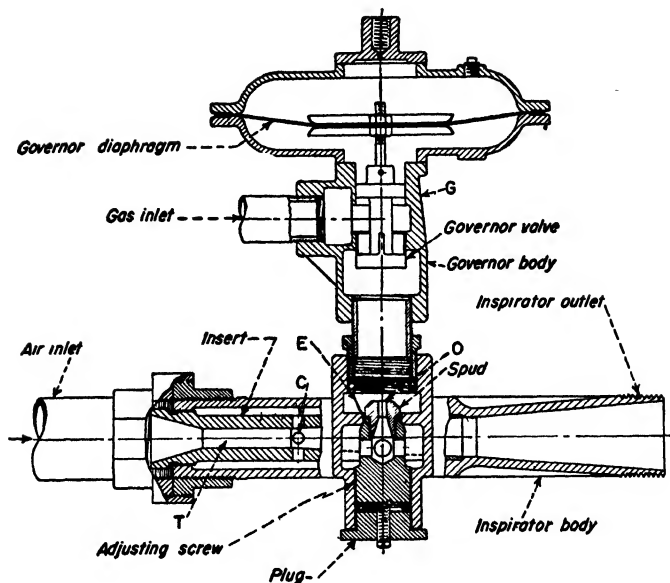


FIG. 24-22. Low-pressure proportioner or inspirator. Gas reduced to zero pressure by the governor is drawn in by the high-velocity air through the insert. (Surface Combustion Corp.)

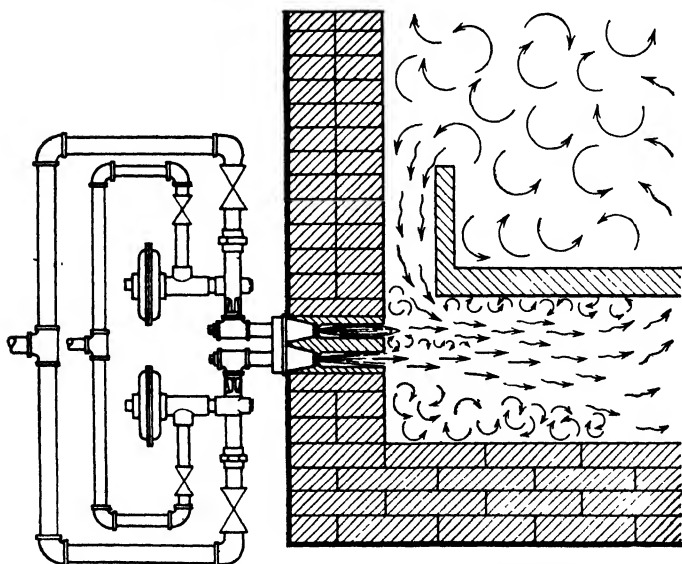


FIG. 24-23. Wide-temperature-range application. Air is injected as indicated, to give a larger volume of hot gases for uniform and rapid heating. At higher temperatures both nozzles function in the usual manner. (Surface Combustion Corp.)

cipitate carbon, as in the manufacture of carbon black. In certain instances, they have also been combined with oil burners to produce suitable forging-furnace flames.

In this system, the gas and air are mixed in proper proportions, compressed, and the mixtures delivered to the burners under pressure. This is the most desirable method of burning gas where exact uniformity of performance is required and careful control

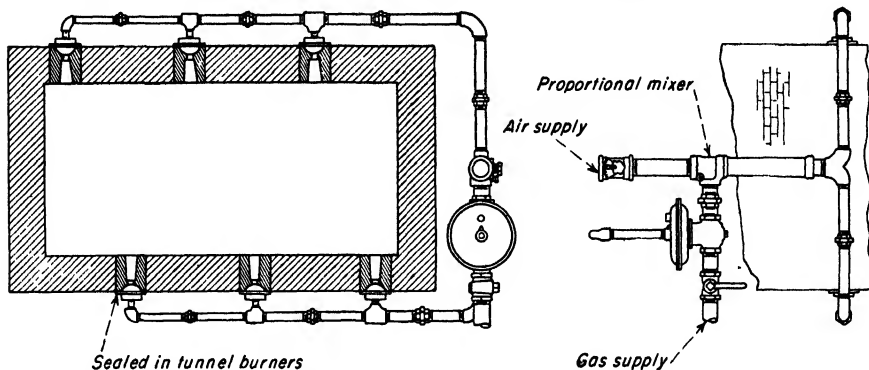


FIG. 24-24. Torch burner, low-pressure proportioner. Typical manifolding and piping layout for multiple burners. (*Hauck Industrial Combustion Data*, p. 65.)

over the heating operations is necessary. An apparatus to accomplish this total premix is shown in Fig. 24-25.

**Partial Premix.** The gas is drawn into the air stream by the kinetic energy of the air under pressure. This system has a wide industrial application. Features are automatic proportioning of air and gas, ease of control through a single (air) valve,

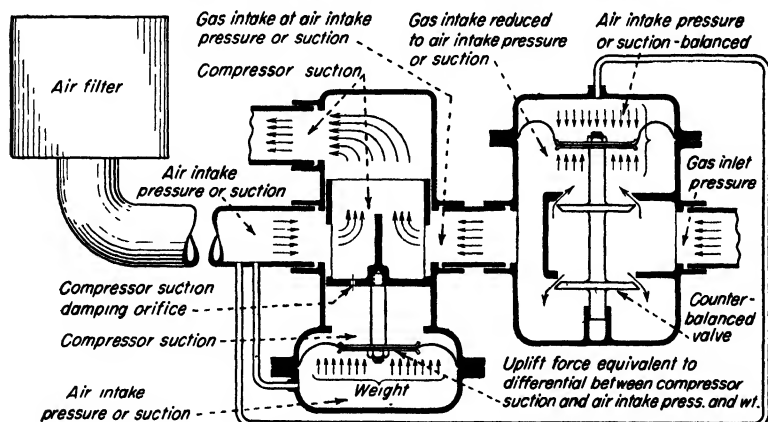


FIG. 24-25. Diagrammatic representation of total premix system. (*Selas Corp. of America.*)

and constant mixture through wide ranges of consumption and turndown. Pressure blowers are available for 4,000 to 200,000 cu ft per hr and 3 to 50 in. water.

**Immersion Torch Burners (Pipe in Fluid).** Solutions and readily fused metals or salts can be heated by the immersion system. The material, contained in a suitable pot, submerges heating tubes, as shown in Fig. 24-26. Torch burners—atmospheric, blast, or premix—fire into the end of the heating tube, which in turn heats the submerging liquid.



Tube heating permits sediment to drop to the bottom and prevents scorching which might occur if the pot were heated from the bottom. Numerous tube arrangements are available.

**Radiant Torch Burners (Pipe in Air).** In this arrangement, the torch burner is fired into the end of a tube that is used to heat air or any other gas that is to be kept free of contamination by the products of combustion.

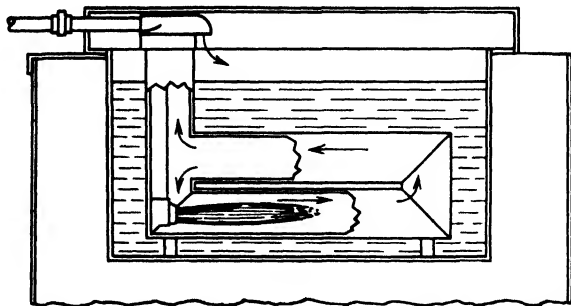


FIG. 24-26. Torch burner, immersion. Tubes are immersed in the liquid being heated. Upper arrow shows vent hood deflecting part of the inert burnt gases over the surface of the pot contents to cut cross formation in metal heating. (*The C. M. Kemp Mfg. Co.*)

**Open-combustion Pipe Burners.** In this type, a pipe is used as the burner and is equipped with drilled holes (see Fig. 24-27) or projecting tube ports or ribbon inserts. The primary air is induced at the mixer at one end of the pipe, and the secondary air is induced around the flame from the surrounding atmosphere. This type is usually an atmospheric burner.

**Open-combustion Ring Burners.** This type of burner consists of rings having suitable drilled holes. These rings are concentric and can be supplied in groups of one to five rings. The rings can be furnished with drilled ports or with projecting drilled ports. Primary air is induced in a mixer on each ring, and the secondary air is drawn in around the flame. Usually this is an atmospheric burner.

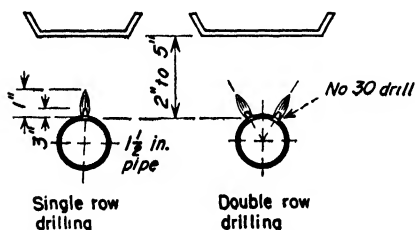


FIG. 24-27. Pipe burners. (*Bryant Heater Co.*)

#### Surface-combustion Types<sup>1</sup>

The so-called surface combustion of gas consists of burning gas, without flame, in contact with an incandescent solid surface.

All surfaces possess, in varying degree, the power of accelerating gaseous combustion. At low temperatures, metallic surfaces of platinum, ferric oxide, and nickel oxide are the best catalysts; at high temperature, incandescent coal and refractory materials are very satisfactory. In commercial applications of surface combustion, a homogeneous mixture of gas and air in the proper quantitative proportions is burned in contact with a localized surface of a solid so that a condition of incandescence is maintained at this surface. The advantages of this system are accelerated rates of complete combustion, with minimum excess air, and rapid rates of heat transfer.

Figure 24-28 illustrates the refractory-bed method of firing. This technique maintains extremely high rates of combustion and completely burns the gases in a

<sup>1</sup> BARNARD, W. N., F. O. ELLENWOOD, and C. F. HIRSEFELD, "Elements of Heat-power Engineering," 3d ed., Vol. II, pp. 557-558, John Wiley & Sons, Inc., New York, 1933.

small zone. The furnace is heated by the hot products of combustion and by the radiation of the incandescent bed. The burner nozzle is protected from high temperature by a special refractory, and any heat transferred to the burner casting is dissipated by the fins. In some cases, the method is being replaced by the refractory-tunnel method.

Figure 24-28 illustrates a surface-combustion tunnel burner. Most of the combustion takes place in the incandescent refractory tunnel. Usually, the tunnel burners are manifold in groups so that one proportioner controls the group.

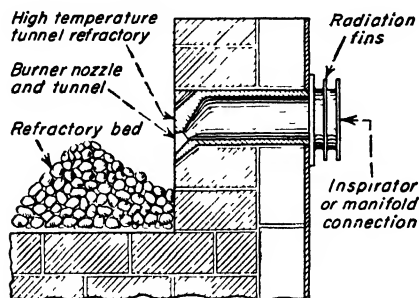


FIG. 24-28. Surface-combustion refractory bed. (*Surface Combustion Corp.*)

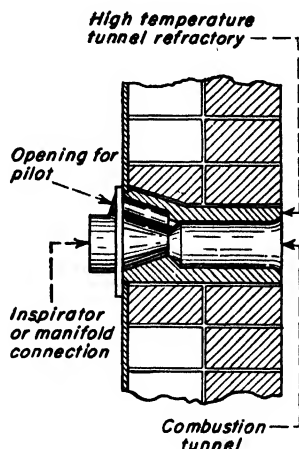


FIG. 24-29. Surface-combustion tunnel burner. (*Surface Combustion Corp.*)

### Submerged-combustion Types<sup>1</sup>

Submerged combustion of a gas can be secured by installing a gas burner, with or without a combustion chamber, directly in a liquid bath. High gas velocities are used in order to prevent backfiring of the flame. In some designs, gas and air are thoroughly mixed and directed into a refractory-lined combustion chamber; ignition is by electric spark. The products of combustion are discharged from the combustion chamber into the liquid bath. Extremely minute bubbles ascend up through the liquid, and a large surface of contact is exposed to give very effective heat transfer.

Submerged combustion has been successfully applied to the evaporation of such liquids as phosphoric and sulphuric acid, to the melting of white metals, to cleaning and dyeing, and to water heating.

Experimentation is still being carried on to determine feasibility of this method for various applications.

### AIR-SUPPLY METHODS

There are many systems of supplying air to the gas burner. The common types can be listed as follows (see Table 24-7 for comparison):

1. Inspirator (atmospheric). Kinetic energy of gas is used to entrain the air, as in a bunsen burner.
2. Partial premix. Kinetic energy of air is used to entrain the gas.
3. Total premix. Gas and air are mechanically mixed in a machine.

**Inspirator or Atmospheric.** The air is drawn into the gas stream by the kinetic energy of the gas stream, as with a bunsen burner, or a venturi-throat injector. If the gas pressure is high enough, sufficient primary air can be supplied by this method to provide complete combustion. The open atmospheric injectors (venturi type) are designed to entrain about 50 to 70 per cent of the total air through the air shutter at

<sup>1</sup> BARNARD, W. N., F. O. ELLENWOOD, and C. F. HIRSHFELD, *op. cit.*

normal gas pressures. (The remainder of the required or secondary air is supplied by the atmosphere around the burner tip.) When 100 per cent air entrainment is desired, the gas pressure must be boosted to at least 4 psi or higher. Since the air injector is normally a part of the burner assembly, illustrations and descriptions are given under Atmospheric Gas Burners.

Table 24-7. Comparison of Air-supply Methods

Type	Mixing process	Auxiliary apparatus required <sup>a</sup>	Pressure		Advantages	Disadvantages
			Air	Gas		
Inspirator (atmospheric)	Kinetic energy of gas to entrain air	None	Atmospheric	3-8 in. water at burner	Simple, inexpensive	Temp range lower, poorer combustion control
Partial premix	Kinetic energy of air to entrain gas	Blower, generally 1 to 2 psi. Check valve on gas line. Gas governor	Generally 1-2 psi	3-8 in. water at governor	Better control and combustion. Higher temp range	More apparatus. More expensive
Total premix	Machine mechanically mixes air and gas, and then mix is compressed. Each installation is generally engineered and designed for a specific application	Mixing machine to proportion gas and air, includes blower. Outlet pressure regulator. Check valve on gas. Fire check valve on outlet mix line	Approx 5 psi  Mixture varies from 1-5 psi	3-8 in. water at governor	Best control and combustion. Highest temp range	Most apparatus. Most expensive

<sup>a</sup> Pressure indicators should be included on all types, as they are of considerable help in operation

### BURNER APPLICATIONS<sup>1</sup>

Burners, with mixing systems of perfect design and proportion, will not be effective unless used in an appliance soundly designed and engineered. No matter what type of equipment application, the heat released must be placed where it will do the most good, so that even distribution will be secured and heat loss will be kept to a minimum. One of the advantages of gas is that it can be readily applied where needed—at the top or bottom, by many small burners or by one large one. The proper venting of the products of combustion is a definite and important part of equipment design and affects performance as well as being a factor of safe operation. Flues and stacks can be sized by the Btu input just as burners can. They should not be either too large or too small; draft conditions must be taken into account and measures taken to prevent back drafts. Heat distribution and transfer can be radically affected by good or poor ventilation of equipment.

**Automatic control equipment** for limiting or controlling temperatures will increase the efficient utilization of the fuel. Many industrial heating operations require close specifications of temperature; even where this is not essential, it is usually wasteful to overheat or underheat or to control by hand where instruments are available.

**Safety instruments**, as well as control, are available. In some cases these are essential to meet building or insurance codes. Off and on control operation calls for safe and automatic ignition, with gas shutoff in case of pilot failure. Many

<sup>1</sup> WEIRUM, C., Considerations Affecting the Sound Utilization of Gas, *Ind. Gas*, vol. 27, No. 7, pp. 7, 23-25, 1949.

recirculation processes call for a purging cycle prior to lighting; and in a great many applications provision must be made to ensure an open damper and a free flue before fuel is turned on. Temperature-limit controls and controls to guard against air or fuel failure are also in common use. It is usually found that the investment required for instrumentation, for both temperature control and safety control, is more than justified in fuel saving, better product, and safety.

Listed in Table 24-8 are the principal methods in common use with typical examples of each, as well as the usual types of burners applied.

**Table 24-8. Typical Methods of Gas Heat Application**

Method	Usual burner type	Examples
Direct flame.	Torch	Speed heating for forging and heat-treating, glass shaping, soldering, brazing
Underfiring . . . . .	Ring, pipe	Boilers, tanks, pot furnaces for melting lead and cyanide heat-treating, varnish kettles
Side firing, direct or tangential	Torch	Retorts, galvanizing kettles, autoclaves
Recirculation, direct and indirect	Torch, pipe	Paint-finishing ovens, tempering furnaces, coffee roasters
Tunnel burners in refractory walls	Torch	Oven heat-treating furnaces, crucible melters
Radiant tubes.	Torch	Low-temp ovens; furnaces up to 1700°F, alloy tubes; high-temp furnaces up to 2400°F, refractory tubes
Immersion tube. . . . .	Torch	Soft-metal melting
Submerged combustion .	Torch	Solution heating

### CONTROL OF FURNACE ATMOSPHERES<sup>1</sup>

**Atmospheric Burners.** Furnaces equipped with atmospheric gas burners can easily be operated with excess-air combustion atmospheres. Owing to the limited burner head pressures available, it would not ordinarily be safe operating practice to attempt production of air-deficient atmospheres with this type of burner. The control of the composition of the atmospheres in such furnaces can best be effected by regula-

**Table 24-9. Reducing Atmospheres Producible by Burning Gas Direct in a Furnace**

	Natural gas		Coke-oven gas	Carburized water gas
	AGA	MCG	AGA	MCG
Max CO, per cent. . . . .	8.4	10.0	12.0	14.0
Max H <sub>2</sub> , per cent. . . . .	8.6	13.0	15.6	25.0
CO <sub>2</sub> , per cent. . . . .	....	5.0	....	3.0
Air supply (per cent total required)	67	52	53	45

NOTE: Size of furnace, insulation, temperature, etc., influence results. AGA = American Gas Association Laboratory. MCD = Michigan Consolidated Gas Co., Detroit.

tion of the burner air shutter and/or the flue-outlet size. To a large extent, controlling the flue size will be more effective than controlling either the primary or the secondary air. This is limited to cases where the supply of secondary air is unrestricted. It may be impossible to maintain successful regulation of furnace atmosphere if secondary air has been restricted by suitable baffles or shields. Then the best regulation of

<sup>1</sup> SHENIDMAN, L., Editor, "Gaseous Fuels," p. 211, AGA, New York, 1948.

the furnace conditions is by means of the flue openings. It probably is possible to reduce the excess air to zero and to produce some degree of the so-called reducing condition; too much effort in this direction may result in smothering the flame. There are also some hazards from possible explosions of pockets of unburned combustible under such conditions. It is not recommended that strongly reducing atmospheres be produced with atmospheric burners.

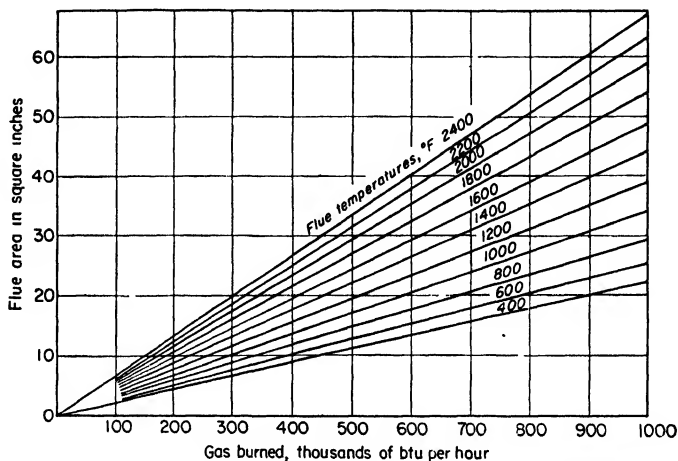


FIG. 24-30. Recommended flue area for gas-fired furnaces. (Hauk Mfg. Co.)

**Pressure Burners.** The control of atmospheres over a wide range of conditions is possible with pressure burners. Since the air-fuel ratios can be regulated as desired, atmospheres with excess air, no excess air, or excess combustible can be produced at will. The limit of burner operation by burner adjustment alone is unknown. Thermal efficiencies are materially reduced by deviations from complete combustion conditions.

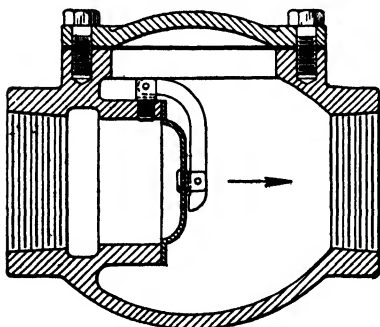


FIG. 24-31. Disk-type check valve. (Norwalk Valve Co., So. Norwalk, Conn.)

maximum line pressures of 150 psi and back pressures of 100 psi. The valve opens wide at  $\frac{1}{2}$ -in. water-pressure loss.

A **diaphragm** check valve is available for those who prefer this type over the disk type.

**Fire check valves** stop the backward travel of any flame in air-gas mixture lines caused by backfiring of burners and automatically shut off air-gas mixture supply

#### GAS-BURNER AUXILIARIES

**Check Valves.** Some form of check valve should always be installed on the gas line partial-premix or total-premix systems. It is used principally for preventing backflash and encroachment of air into gas lines (where it then becomes a potential explosion hazard) when air pressure exceeds gas pressure. They can also be used where a reverse flow of gas or air must be prevented.

A disk type is shown in Fig. 24-31. The disk is of lightweight construction and offers less resistance than the standard-weight check-valve construction. This valve is for

feeding such flame. In the Selas valve, the flame traveling back in the air-gas line comes to the fire check valve. A screen stops the flame, and the flame burning or lingering on the screen heats up bimetallic strips that release the close-off valve. A check valve included in the system reacts to any explosive back pressure and gives protection against the damaging results of pressure waves. The fire check should be located as close to the burner as possible, or to any starting point of a backfire. Figure 24-32 gives the pressure drop vs. capacity of some fire checks.

**Gas-burner ignition methods** can be listed under two types, hand torch and pilot.

A simple **hand torch**, where gas is available at the burner, can be made from a suitable length of small-bore pipe securely connected by means of a rubber hose to the

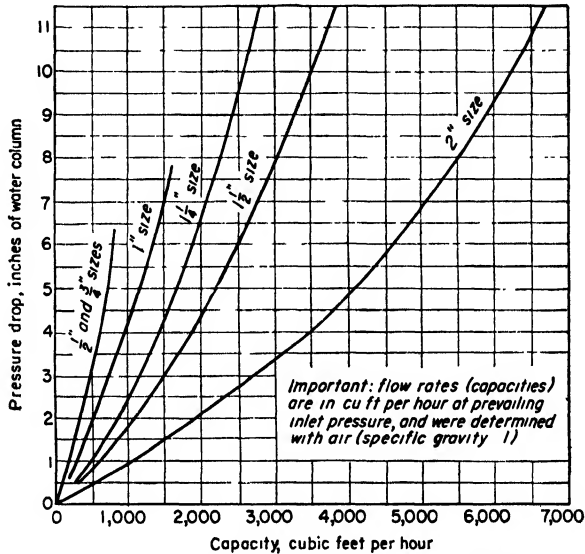


FIG. 24-32. Pressure drop vs. capacity, fire-check valve. (Selas Corp. of America.)

gas source. The torch is lighted and then poked through a suitable access port close to the burner. As soon as the burner gas valve is turned on, the lighted torch ignites the burner. A similar torch can be made from a piece of asbestos rope firmly fastened to the end of a heavy wire. This torch is dipped in kerosene, ignited, and poked through the access hole at the burner.

The pilot types can be subdivided as follows:

1. **Constant flame.** This consists of a fixed small-bore tube led to the burner from the gas source. This pilot is kept lighted. When the gas is admitted to the burner, this pilot ignites it. The pilot is lighted manually or by spark.
2. **Hand pilot.** This consists of a portable small-bore tube or pipe used as a lighting torch, supplied by a securely connected rubber hose attached to the gas supply. This torch is first lighted manually; the burner is turned on and ignited from the torch. The torch is turned off or used for other burners.
3. **Cyclic spark.** A device which sets off a high-tension spark at set intervals to ensure that the burner is lighted and which consequently promotes greater safety.



## CHAPTER 25

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### SOME SPECIFIC NON-STEAM-MAKING USES OF FUEL

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## SINTERING FINE ORES

Sintering is fundamentally a process of agglomerating fine ores by clinkering so that the resultant sizes will be sufficiently large for blast-furnace use. (Other properties are essential for sintering, as will be discussed.) In mining, ores of relatively low metal content may frequently be beneficiated after grinding, such as by magnetic or chemical means. The ground beneficiated material is then prepared for smelting by sintering. Flue dust is also frequently reclaimed by sintering.

In practice, sintering is accomplished on one of two types of equipment, the Dwight Lloyd continuous process and the Greenawalt batch process.

### Equipment for Sintering

The Dwight Lloyd (Fig. 25-1), which is widely used, consists mainly of an induced-draft traveling grate up to some 80 ft in length. A charge, after being properly

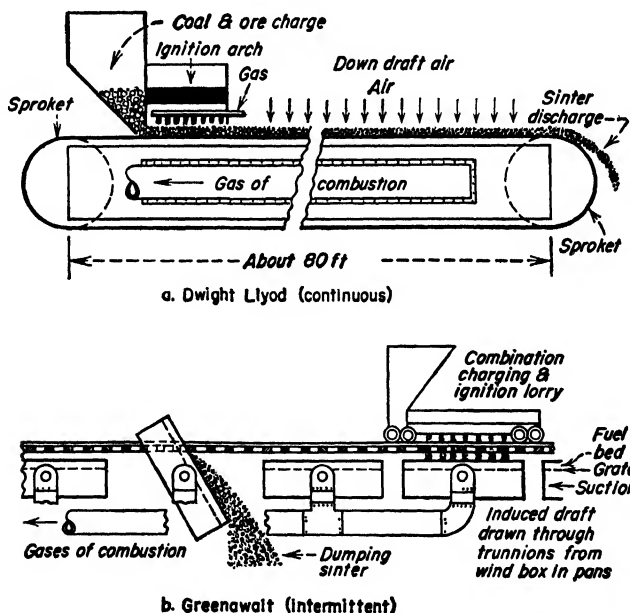


FIG. 25-1. Schematic arrangement of Dwight Lloyd and Greenawalt sintering machines.

prepared from several carefully proportioned materials, is laid on the grate and ignited by down-blast oil or gas jets covering the grate for the first few feet of travel. The remainder of the grate is then available for the burnout with self-sustaining combustion. Because all air for ignition is drawn through the fire, the top of the fuel bed is relatively cool and the sintering bed is operated without any covering, hood, or other obstruction over the length of the grate.

The **Greenawalt** system (Fig. 25-1), of which the Bethlehem Steel Co. operates an outstanding example at its Lebanon, Pa., plant, is the same in principle, with the important difference that sintering takes place in large flat "pans" some 15 to 20 ft square. The charge is laid down and ignited by special wide-gauge cars straddling

the series of pans. When the sintering is complete, the entire pan, pivoting on trunnions, is dumped into railroad cars beneath.<sup>1</sup>

### Fundamentals of Sintering

In a paper presented at the Buffalo meeting of AIME, in April, 1938, John E. Greenawalt described the fundamentals of sintering iron ore.<sup>2</sup> Some of the high lights of this paper follow:

Broadly speaking, sintering is an oxidizing or burning process, and, therefore, the volume of air passing through the charge is an all-important factor. Air must be passed through the charge in sufficient volume to produce a sintering temperature in the mass as influenced by the porosity of the charge itself and the suction available to force the air current through the pores of the charge.

**Porosity of the charge** is influenced by three factors:

**1. Moisture**, without which the porosity would be impractical to pass sufficient air, progressively increases porosity until a maximum is reached; then, if we continue to add water, it decreases porosity until completely destroyed. In practice, moisture varies with the character of the ore and may range from 5 to 12 per cent. Magnetite ores require the least and clayey ores the most. Drier charges tend to produce a slightly more fragile sinter, wetter charges stronger and denser sinter. High moisture decreases combustibility and complicates ignition.

**2. Returning part of the sintered fines.** As it is impractical to produce 100 per cent sinter in one operation, all the fine material below a fixed size is returned and resintered. The size of these "return fines" may vary from  $\frac{1}{4}$  to  $\frac{3}{4}$  in., and the amount may vary from 20 to 50 per cent, with an average of about 25 per cent for the intermittent systems. The addition of "return fines" increases porosity, sintering qualities, and thus capacity. The practice has the disadvantage of requiring double sintering with additional fuel consumption, and also strongly tends to increase the formation of undesirable iron silicates.

**3. Preparing the charge of a mixture of materials, some coarse and of great permeability.** This method of increasing the porosity is very desirable wherever it can be applied, *e.g.*, mixing fine ores with flue dust, roll scale, etc. It is also advantageous to mix fine magnetic concentrate with coarser ores in the preparation of the sintering charge.

**Thickness of Charge.** Having prepared the charge so as to obtain maximum porosity, we find a definite resistance to the flow of air through the charge, proportionate to the thickness of the charge and to the suction available. With the intermittent system, the depth of the charge varies from 7 in. with a fine magnetic concentrate to 18 in. with the fines below  $\frac{3}{8}$  in. of a hematite ore. Economically a thick charge has many advantages over a thin layer, the cost of igniting is the same, and less sintering fuel is needed.

**Suction.** The thickness of the charge is also dependent upon the suction. Powerful fans capable of giving a maximum suction of some 50 in. water are commonly used for the intermittent process. Figure 25-2 illustrates the yields obtained by Greenawalt with various suction conditions. It will be noted that, by increasing the suction from 17 to 40 in., the yield was increased 145 per cent. To apply high suction, it is obvious that the sintering apparatus must be airtight from the top surface of the charge to the fan exhauster.

**Time of Sintering.** The time of sintering, *i.e.*, the time required for the sintering zone to travel from the top surface of the charge to the grate, varies from 10 to 18

<sup>1</sup> JOHNSON, ALLEN J., "New Horizons for Anthracite," Fifth Annual Anthracite Conference of Lehigh University, pp. 190-193, 1947.

<sup>2</sup> As summarized by SWEETSER, RALPH H., "Blast Furnace Practice," pp. 96-104, McGraw-Hill Book Company, Inc., New York, 1938.

min. Experience has shown that 18 min should be a maximum; for, if more time is required, the portion of the charge near the grate dries out to retard the travel of the sintering zone. The sintering zone should travel through the charge at about 1 in. per min.

**Proper ignition** is important, and the time required to accomplish this should not exceed 30 sec. Long exposure of the igniting surface to the flame dries out the charge and produces uneven sintering. A clean high temperature and highly oxidizing flame applied instantly to every square inch of the surface produces best results. For this reason, it is preferable to use a high-grade fuel such as oil or natural or coke-oven gas instead of blast-furnace or producer gas.

**Grates.** In any downdraft sintering apparatus, the grate receives severe punishment. It should be self-cleaning and have a free-air opening amounting to at least

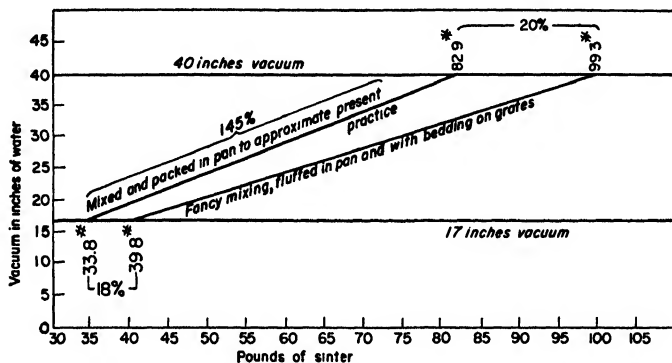


FIG. 25-2. Results obtained by applying increased suction to sintering apparatus. Conclusions from tests: Fancy mixing, fluffing, and bedding increased sinter tonnage 18 to 20 per cent. Vacuum in normally packed pan increased tonnage 6 per cent per inch, or from 17 to 40 in., an increase of 145 per cent. Vacuum combined with fluffing and bedding increased tonnage 8 per cent, or from 17 to 40 in., an increase of 194 per cent. (*John E. Greenawald, based on tests by A. K. Walter, Blast Furnace Practice.*)

20 per cent of the total grate area. The amount of grate opening depends, however, on the character of the material being sintered. Fine ores lacking in cohesiveness are readily drawn through the grate by the air blast. Whenever possible, it is advisable to place a thin layer of coarse material upon the grate; and, when sintering fine ores, it is advisable to place a layer of the ore upon the grate without the admixture of fuel or with very little fuel. This prevents the formation of highly fused sinter which frequently forms next to the grate.

**Cooling Sinter.** Sinter should be air-cooled as, if hot sinter is doused with water, it becomes very brittle and breaks up easily when handled. Air-cooled sinter is much stronger than water-cooled sinter. Sinter made with lime-content charges should not be moistened.

**Fuels for Sintering.** Anthracite fines are excellent fuels for sintering, as is coke breeze crushed to pass a 10-mesh screen. Because of availability, anthracite is the preferred fuel. Bituminous coal is not satisfactory because of its volatile constituents, which are not only wasted but cause tarry compounds which clog the pores of the charge to greatly reduce air flow through the bed. To obtain uniform distribution throughout the charge and avoid intense local temperatures, the fuel must be finely divided. There is not sufficient time to burn the larger particles of fuel, and the unburned fuel is therefore wasted.

**Self-fueling Ores.** Ores containing 6 per cent sulphur have sufficient fuel to produce a sintering temperature. Blast-furnace flue dust always has an excess of fuel for sintering; in fact a ton of dust with 15 per cent of carbon has sufficient fuel to sinter  $3\frac{1}{2}$  tons additional of fine ore or concentrate, provided that the charge is properly arranged and treated with high suction.

**Quality of Sinter Desirable.** Reversing earlier opinions that the strength of sinter is increased by silica, Greenawalt concludes that the problem is one of converting all kinds of ores into a sufficiently strong sinter for blast-furnace use without the forma-

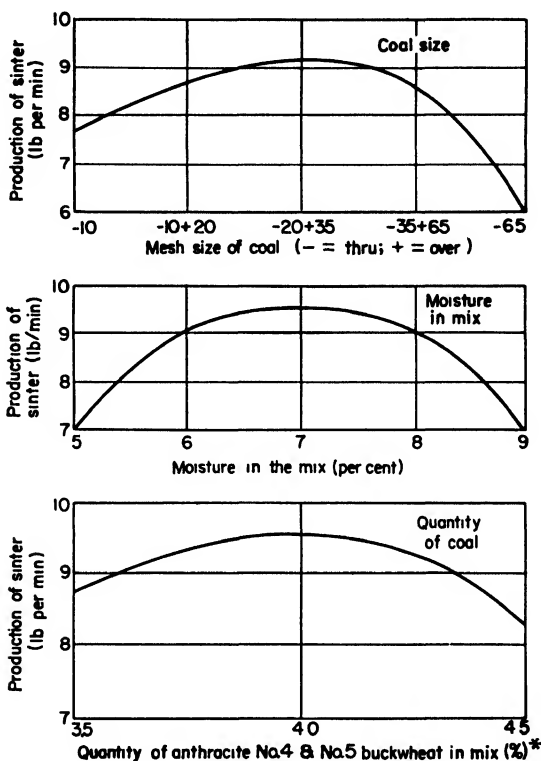


FIG. 25-3. Effect of coal quantity, size, and moisture on sinter produced for 65-mesh magnetite. (Stanley & Mead.)

tion of iron silicates. The factors involved in the avoidance of iron silicates are the control of the temperature at which sinter occurs and the time the charge is exposed to this temperature, the amount of returned fines in the charge, and probably the presence of small quantities of basic materials in the charge.

**Hematite Results.** Greenawalt reports high-suction carefully blended charges of red hematite ore as excellent. Sinter strong enough for blast furnaces was repeatedly made with  $3\frac{1}{2}$  per cent coke charge. Excellent sinter was made by adding 15.41 per cent of flue dust, so that the charge sintered contained only 2.84 per cent carbon, this being considerably less than one-half the amount of fuel heretofore required for this ore. The fines below  $\frac{1}{4}$  in. amounted to 20 per cent and were returned to the succeeding charge. A 16-in. charge was sintered in 15 min.

## Summarization of Sintering Results

Stanley and Mead<sup>1</sup> concluded, as a result of comprehensive tests, that the best quality and quantity of sinter were obtained with the following mix:

1. 4.0 per cent coal
2. 25.0 per cent return fines ( $-10$  mesh  $+ 0$ ) (at least 18.75 per cent  $-10$  mesh  $+ 35$  mesh)
3. 70.3 per cent magnetite ( $-65$  mesh size)
4. 0.7 per cent slaked lime

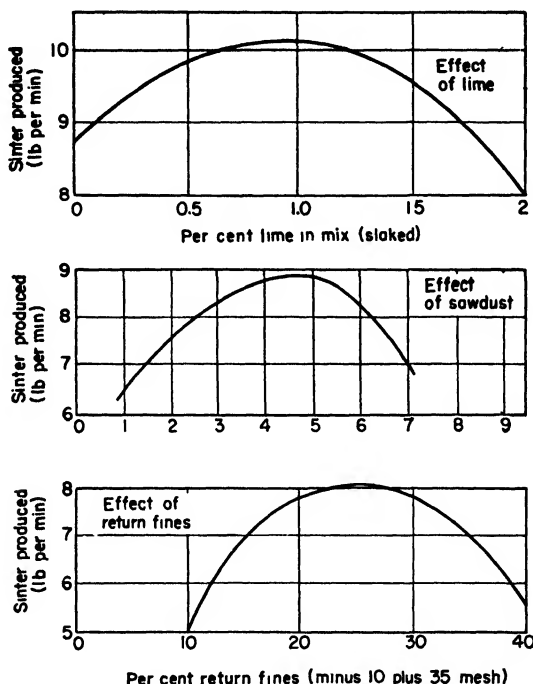


FIG. 25-4. Effect of lime, sawdust, and return fines on sinter produced for 65-mesh magnetite. (Stanley & Mead.)

The average test production on the above mix was 9.9 lb per min of 246 lb/hr/sq ft grate area. This is slightly higher than average production in the sintering plant pans on  $-20$  magnetite.

The pilot-plant work indicated that  $-65$  magnetite can be sintered in the sinter plant if close control can be maintained over the following items: (1) adequate amount of bedding material ( $-1$  in.  $+ \frac{1}{2}$  in. return fines for hearth layer), (2) sized return fines ( $-10$  mesh  $+ 0$ ), (3) anthracite coal (size and moisture percentage), (4) moisture percentage in the mix, (5) magnetite moisture content, and (6) percentage of magnetite, coal, lime, and return fines in the prepared feed to the plant. The results show that a more accurate control on over-all operation will be necessary for sintering 65-mesh magnetite than is needed at present for sintering  $-20$  magnetite.

<sup>1</sup> STANLEY, ALAN, and JOSEPH C. MEAD, Sintering Characteristics of Minus Sixty-five and Twenty Mesh Magnetite, *Mining Trans. AIME*, June, 1949, pp. 181-186.

## GAS TURBINES

The potentialities of transforming heat into power direct, without the use of boilers as intermediaries, has intrigued designers for centuries, but it is only within the past decade that practical results have been achieved. Even now, the modern gas turbine is a combination of basic elements which has been known for years but which could not be economically or advantageously combined because their degree of individual perfection had not reached the point of perfection demanded by the acceptable gas turbine.

In its basic form, the gas turbine consists of a turbine into which hot gases of combustion are introduced as a motive force after having been compressed by a part of the power available from the turbine. Actually this simple cycle is subject to many refinements of multiple combustion chambers, intercoolers, regeneration, reheat, etc., all designed to improve effectiveness and efficiency. Further, as the gas turbine is still definitely in the experimental stages, despite several very successful applications, no pattern of design has as yet emerged which can be considered standard. Table 25-3 as compiled by *Power* lists the elements and performance of most of the known gas turbines and thus serves to show results with several combinations.

**Advantages of Gas Turbines.** For each application the gas turbine presents different characteristics and different advantages. It is compact for locomotives and does not require water; it increases the available power for ships; it drives airplanes faster; and for power plants it is complete within itself without major auxiliaries. For process industries, it is a compressor or expander, a waste saver, or a heat absorber.

A further advantage lies in the fact that the power of a gas turbine increases rapidly as the inlet-air temperature to the compressor drops. Thus the aviation gas turbine, operating in the bitter cold upper atmosphere, is at a distinct advantage. In Arctic climates, the absence of both steam and water eliminates freezing, and, in fact, the colder the weather, the better it works.

Other advantages are light weight, compactness, simplicity, and the absence of reciprocating parts.

**Adaptability to Various Fuels.** As the gas turbine operates on the heat in the gases of combustion from the fuels, the source of such heat is immaterial. Thus, as far as the turbine is concerned, any gaseous, liquid, or solid fuel may be used with virtually the same results. Actually, however, when coal is used a fly-ash separator must be inserted between the combustors and the turbine. The resultant increased pressure drop will lower the efficiency somewhat.

**Gas Temperatures.** The gas turbine can increase the output of a diesel engine by as much as 50 per cent when operating as a supercharger with temperatures not exceeding 1000°F. However, as a prime mover, the field for gas turbines is very narrow below 1000° and should be at least 1100°F for practical application. As thermal efficiency increases rapidly with increased inlet temperatures (16 to 18 per cent at 1000°F; 30 per cent at 1200°F), it is highly advantageous to design gas turbines for as high inlet temperatures as is permitted by the materials of turbine construction. At 1500°F it is estimated that gas turbines will have thermal efficiencies surpassing those of the diesels (thermal efficiency of diesels usually 30 to 34 per cent; steam turbines 20 to 25 per cent or 30 in most efficient central stations).

### Analyzing Turbine Performance<sup>1</sup>

In analyzing the performance of the various gas-turbine cycles, it is necessary to take into account three factors: (1) the efficiency, (2) the air rate, and (3) the work ratio.

<sup>1</sup> SAWYER, R. TOM, "The Modern Gas Turbine," Prentice-Hall, Inc., New York, 1945. Reprinted by permission.

The **efficiency** of the cycle determines the effectiveness with which heat is used; it is defined as the ratio of net power output from the prime mover to the external heat supplied to the combustion chambers.

The **air rate**, expressed in pounds per horsepower per hour, is analogous to the steam rate of a conventional turbine plant and represents the quantity of fluid per unit of power output.

The **work ratio** represents the proportion of total installed turbine power usefully delivered to the shaft. A plant operating with a work ratio of 0.4 develops 400 hp for each 1,000 hp of installed turbine capacity, the remaining 600 hp being used to supply the compression and to overcome the parasitic losses.

The air rate, by its measure of the amount of air required, and the work ratio, by its measure of the amount of power required, are useful in judging the amount of equipment necessary for the plant as a whole. The ideal would be high efficiency, low air rate, and high work ratio.

In general, the **air rate** will range between 60 and 75 at 1200°F; 46 and 60 at 1350°F; and 37 and 52 at 1500°F (1-0- $n_r$  cycle).

The **work ratio** will range between 25 and 40 at 1200°F; 33 and 45 at 1350°F; and 37 and 50 at 1500°F (1-0- $n_r$ ) cycle.

**Nomenclature of Gas Turbines.** A method of describing gas-turbine cycles, originally suggested by A. Lysholm, chief engineer, Aktiebolaget Ljungstrom Angturbin, Sweden, consists of a three-number designation. The first number represents the number of combustion chambers, which is equal to the number of turbine expansions; the second number is the number of intercoolers, which is equal to the number of compressor stages less one; the third number represents the effectiveness of the regenerator or air preheater in the system. Thus 2-1-0.75 refers to a turbine system with two combustion chambers or turbine expansions, one intercooler between two compression stages, and a regenerator efficiency of 0.75.

### Description of Components

**Heat Exchanger or Regenerator.** This is a radiator heat exchanger placed in the path of the exhaust gases from the turbine to transfer a part of their heat to the

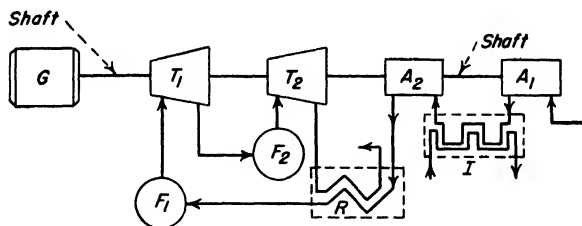


FIG. 25-5. Arrangement of components of gas turbine.  $G$  = generator;  $T_1$  = high-pressure turbine;  $T_2$  = low-pressure turbine;  $F$  = fireboxes (combustors);  $A_1$  = low-pressure air compressor;  $A_2$  = high-pressure air compressor;  $R$  = regenerator;  $I$  = intercooler.

incoming cool air. They may be designed for any degree of effectiveness; in general, this is decided by weight and space considerations, small (or none) for aviation, medium for locomotive and marine, and large for stationary service.

**Intercoolers.** Intercoolers are air-to-air heat exchangers placed between the compression stages to increase the efficiency of compression.

**Reheaters** are supplementary combustion chambers placed in the path of the hot exhaust gases between the successive turbine stages to improve the results from the succeeding stages.

The first stage of intercooling may be expected to improve optimum performance 5 to 6 per cent, the first stage of reheat an additional 7 to 9 per cent. Further stages will improve performance but at a diminishing rate. (See Figs. 25-5, 25-6.)

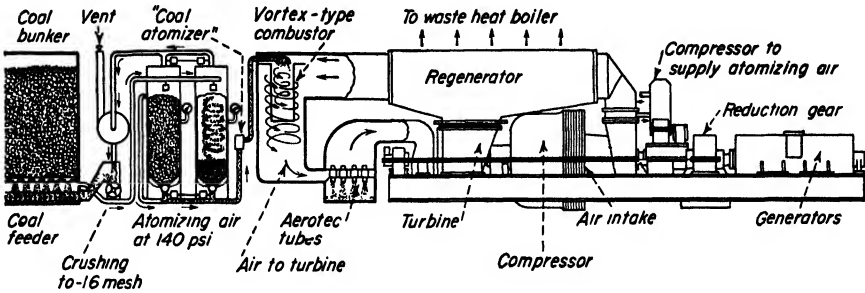


FIG. 25-6. Arrangement of components for gas-turbine locomotive. (*Bituminous Coal Research, Inc.*)

Table 25-1. Operating Conditions, Gas-turbine Combustors<sup>1</sup>

	Locomotive unit, as tested	Typical aircraft engine
Outlet-gas temp, deg F . . . . .	1300	1500
Temp rise, deg F . . . . .	800	1100
Pressure, psia . . . . .	87	60
Air flow per chamber, lb/sec . . . . .	15.6	9
Fuel . . . . .	Bunker C	Kerosene
Pressure drop (impact to impact), per cent . . . . .	6	4.5
Combustion efficiency, per cent . . . . .	98	98
Max exhaust temp, starting, deg F . . . . .	900	1500
Heat release, Btu/hr/cu ft $\times 10^6$ . . . . .	5.9	13

<sup>1</sup>BUCKLAND, BRUCE O., and DONALD C. BERKLEY, "Combustion System for Burning Bunker C Oil in a Gas Turbine," ASME Paper, 48-A-109, annual meeting, December, 1948.

Table 25-2. Effect of Air and Inlet Temperatures<sup>1</sup>  
(Pressure ratio 6:0)

Turbine inlet temp, deg F	Air inlet temp, deg F	Cycle designation			
		1-0-0	1-0-0.75	2-0-0.75	2-1-0.75
1200	100	23.3	22.1	26.6	30.5
	70	21.9	25.2	29.1	32.6
	40	23.4	28.2	31.6	34.6
1500	100	24.3	31.1	33.8	36.5
	70	25.2	33.4	35.7	38.1
	40	26.1	35.6	37.5	39.7

<sup>1</sup>Reprinted by permission of Prentice-Hall, Inc., from "The Modern Gas Turbine," 2d ed., by R. Tom Sawyer, copyright 1945 by Prentice-Hall, Inc.



Table 25-3. Design Survey of Gas Turbines<sup>1</sup>

Location	Builder	Status	Remarks
Experimental and Shop Units			
1. U.S. Naval Engineering and Experimental Station, Annapolis, Md. . . . .	AC	1944	Turbines in parallel
2. Boeing Airplane Co., Seattle, Wash. . . . .	DL	T	Turbines in series, 2,500 rpm
3. DeLaval Steam Turbine Co., Trenton, N.J. . . . .	DL	T	Marine design, reversible
4. DeLaval Steam Turbine Co., Trenton, N.J. . . . .	DL	C	3-stage output turbine
5. John Brown Co., Ltd., Clydebank, Scotland . . . . .	JB	1948	Designed by Pametrada
6. Brush Elec. Eng. Co., Loughborough, England . . . . .	BE	C	Stator cooling
7. English Elec. Co., Ltd., Rugby, England . . . . .	EE	1944	
8. Metropolitan-Vickers, Trafford Park, England . . . . .	MV	1949	Power plant for M-V works
9. C. A. Parsons Co., Ltd., Heaton Works, England . . . . .	P	T	
10. Pametrada (experimental marine unit) . . . . .	PT	....	Components by various firms
11. Ruston & Hornsby, Ltd., Lincoln, England . . . . .	RH	1949	
12. Escher Wyss, Ltd., Zurich, Switzerland. . . . .	EW	1939	9-stage low-pressure compressor 13-stage high-pressure
13. Maschinenfabrik, Oerlikon, Zurich, Switzerland . . . . .	O	1947	
14. Sulzer Bros, Ltd., Winterthur, Switzerland . . . . .	S	1948	Closed part of cycle 4:1
15. Sulzer Bros, Ltd., Winterthur, Switzerland . . . . .	S	1945	
16. Électricité de France, Vitry, France. . . . .	M	T	Test plant, Vitry steam station
17. Cie Électro-Mécanique, Le Bourget, France . . . . .	EM	T	Only high-pressure elements survive
18. SEMA and SIGMA, Venissieux, Rhône, France . . . . .	SM	1949	Output turbine by Alsthom
19. Laboratoires Turbine à Gas, St. Denis, France . . . . .	T	1949	Turbine only, compressed air
Stationary Units			
20. Tennessee Gas Transmission Co., Moorehead, Ky . . . . .	CF	B	To drive pipe-line compressor
21. Huey Sta. Okla. Gas & Elec Co., Oklahoma City . . . . .	GE	1949	Exhaust heats feed water
22. Farmingdale Sta., Central Maine Power Co. . . . .	GE	1949	Replaces steam unit
23. Bangor Hydroelectric Co., Bangor, Me. . . . .	GE	1950	Supplements hydro system
24. Public Service Co. of Oklahoma (2 units) . . . . .	GE	1950	
25. Mississippi River Fuel Corp., pipe line (test) . . . . .	W	1946	Locomotive prototype
26. Carolina Port Sta., N. Scotland Hydro Bd . . . . .	JB	1950	Under Escher Wyss license
27. Trafford Sta., British Electricity Authority . . . . .	MV	1950	
28. Dunston Sta., British Electricity Authority . . . . .	P		
29. National Gas-turbine Estab., Pyestock, England . . . . .	P		
30. Municipal Elec. Supply, Neuchatel, Switzerland . . . . .	BB	1939	
31. Anglo Iranian Oil Co., Agha-Jari, Iran (2 units) . . . . .	BB	1949	Fuel gas expanded separately
32. Corp. Peruano del Santa, Chimbote, Peru . . . . .	BB	1948	Stand-by unit
33. Filaret Station, Bucharest, Rumania . . . . .	BB	1948	
34. Santa Rosa Sta. Lima Lt. Pwr. & Trwy. Co., Peru . . . . .	BB	1949	Base-load unit
35. C. A. Venzolana de Cementos, Caracas (2 units) . . . . .	BB	1949	
36. Raymond Archache & Co., Alexandria, Egypt . . . . .	BB	1949	
37. Bernau Sta. North East Power Co., Switzerland . . . . .	BB	1948	Winter backup of hydro
38. Bernau Sta. North East Power Co., Switzerland . . . . .	BB	1949	Double flow low-pressure turbine, compressor
39. St. Denis Sta., Électricité de France, Paris . . . . .	EW	1949	Last 2 compressor stage, centrifugal
40. Weinfelden Sta. North East Power Co., Switzerland . . . . .	S	1950	Winter backup of hydro
41. Électricité de France, Paris, France . . . . .	M	1949	
42. Rheims Sta. Électricité de France, Rheims . . . . .	SM	1950	
43. St. Denis Sta. Électricité de France, Paris . . . . .	R		

NOTE: Symbols are grouped on pp. 869 and 872.

<sup>1</sup> Power, August, 1949.

Table 25-3. Design Survey of Gas Turbines—(Continued)

Location	Builder	Status	Remarks
Locomotive Units			
44. Loc. Dev. Com. Bituminous Coal Research, Inc .	AC	1949	American Locomotive Co., to build chassis
45. Loc. Dev. Com. Bituminous Coal Research, Inc	E	....	Baldwin Locomotive to build chassis
46. Atchison Topeka & Santa Fe Railway Co . . . .	E	....	Baldwin Locomotive to build chassis
47. General Electric Co., Schenectady, N.Y . . . . .	GE	1948	Union Pacific to test
48. Westinghouse Electric Co., Philadelphia (2 units).	W	1949	4,000-hp demonstrator locomotive
49. British Railways, western region . . . . .	MV	1950	
50. Swiss Federal Railways . . . . .	BB	1941	Over 100,000 miles, 7,000 hr
51. British Railways, western region . . . . .	BB	1949	
52. Brown, Boveri Corp. (experimental unit) . . . .	BB	T	Unit has "Compresz"
Marine Units			
53. U.S. Navy (2 units, vessels unidentified) .	E	C	
54. U.S. Maritime Commission (merchant vessel)			
55. Anglo-Saxon Petroleum Co., tanker <i>Auria</i> .	BT	C	Replaces 1 of 4 diesels
56. British Admiralty ("Captains" class frigate) .	MV	1947	
57. British Admiralty (motor gunboat MGB-2009) .	MV	1947	First gas turbine used at sea

## Explanation of Symbols in Tables 25-3 and 25-4

## Builders of Gas Turbines:

AC: Allis-Chalmers Mfg. Co., Milwaukee, Wis.  
 B: Boeing Airplane Co., Seattle, Wash.  
 BB: Brown, Boveri & Co., Ltd., Baden, Switzerland  
 BE: Brush Electrical Engineering Co., Loughborough, England  
 BT: British Thomson-Houston Co., Ltd., Rugby, England  
 CF: Clark Bros. Co., Inc., Olean, N.Y. (manufacture), and Frederic Flader, Inc., North Tonawanda, N.Y. (design and development)  
 DL: DeLaval Steam Turbine Co., Trenton, N.J.  
 E: Elliott Co., Jeanette, Pa.  
 EE: English Electric Co., Ltd., Rugby, England  
 EM: Cie Electro-Mécanique, Le Bourget, Seine, France  
 EW: Escher Wyss Engineering Works, Zurich, Switzerland  
 GE: General Electric Co., Schenectady, N.Y.  
 JB: John Brown & Co., Ltd., Clydebank, Scotland  
 M: Designs by Ernest Mercier and associates; builders unidentified  
 MV: Metropolitan-Vickers Elec. Co., Trafford Park, England  
 O: Maschinenfabrik Oerlikon, Zurich, Switzerland  
 P: C. A. Parsons & Co., Ltd., Newcastle-upon-Tyne, England  
 PT: Design by Pametrada (Parsons and Marine Engineering Turbine Research and Development Association); components by various firms  
 R: Société Rateau, Corneuve, France  
 RH: Ruston & Hornsby, Ltd., Lincoln, England  
 S: Sulzer Bros., Ltd., Winterthur, Switzerland  
 SM: Research and development by SEME (Société d'Etude Mécaniques et Energetiques) and manufacture by SIGMA (Société Industrielle Generale de Mécanique Appliquée) of Lyons-Venissieux-France  
 T: Turbomeca, Bordes par Pau, Basses Pyrénées, France  
 W: Westinghouse Electric Corp., Philadelphia, Pa.

## Symbols for Status:

B: Order booked  
 C: Under construction  
 Cycle:  
 C: Closed cycle  
 EP: Equipressure cycle  
 FP: Free-piston cycle  
 O: Operating  
 T: Under test  
 O: Open cycle  
 S: Semiclosed cycle

(Continued on page 872)

Table 25-4. Design Survey of Gas Turbines

General characteristics											Fuel		Performance			Turbines			Compressors									
No.	Name, plate or rated capacity	Turbine-inlet temp, deg F	Pressure ratio	Cycle	No. shafts	Shaft speeds, 1,000 rpm	No. cylinders	Cylinders in series	Compressor cylinders	Compressors in series	Intercoolers	Heating stages	Combustor type	Regenerator effectiveness, per cent	Type	Btu, net	Thermal efficiency, per cent	Work ratio	Air rate cfm/kwhr	Impulse stages	Reaction stages	Engine efficiency, per cent	Blade or disk cooling	Type	No. stages	Discharge pressure, psia	Compression efficiency, per cent	
1	3,500 hp	1500	4.0	O	2	5 18-5 18	2	0	1	0	0	1	D	80	DO	..	..	..	..	2	3	0	..	Disk	A	20	59	85
2	200 hp	1500	...	O	2	36 0-24 0	2	2	1	0	0	1	D	0	O	..	..	..	..	1	0	..	..	Disk	C	1	..	..
3	750 hp	1500	...	O	3	21-17-13 6	3	2	2	2	0	1	M	0	O	18,500H	17.6	..	..	..	0	5	..	None	M	2	..	81
4	3,000 hp	1300	6.0	O	2	7 9-4 2	2	2	1	0	0	1	S	0	O	..	..	..	..	7	0	..	..	None	A	21	52	..
5	500 hp	1200	3.5	O	2	1 6 0	2	2	1	0	0	1	S	65	O	18,600	17	0.38	19 5	2	0	85	..	Disk	A	16	71	82
6	2,000 kw	1160	4.9	O	2	5 0-3 0	2	2	1	0	0	1	S	0	O	18,350	40	0.26	24 7	2	0	..	..	Disk	A	11	51	86
7	150 hp	1000	4.75	FP	1	10 0	1	0	1	0	0	1	S	..	O	..	15.67	0.34	56	1	0	87	..	Both	A	25	..	81
8	2,000 kw	1200	3.5	O	2	7 3-5 0	2	2	1	0	0	1	S	75	O	18,288	31.57	0.39	73C	6	0	..	..	..	A	7	..	88
9	500 hp	1200	4.0	O	1	1 6 0	1	0	1	0	0	1	S	75	O	..	..	..	..	..	..	..	..	..	A	3	..	..
10	3,500 hp	1200	5.5	O	2	4 5-3.08	2	2	2	2	1	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	..	..	..
11	1,100 hp	...	...	O	2	...	2	2	3	3	2	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	..	..	..
12	2,000 kw	1270	3.8	C	2	8 0-3 0	2	2	3	3	2	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	7	..	..
13	1,000 kw	...	4.0	S	2	4 5-3 0	2	2	3	3	2	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	3	..	..
14	7,500 hp	1200	16	S	3	...	4	3	3	3	2	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	..	..	..
15	7,000 hp	...	...	FP	...	...	...	...	...	...	...	...	...	...	...	..	..	..	..	..	..	..	..	..	A	15	..	..
16	1,000 hp	...	...	EP	...	...	...	...	...	...	...	...	...	...	...	..	..	..	..	..	..	..	..	..	A	..	..	..
17	10,000 hp	1470	...	DP	3	6 3-5 56-3 6	3	3	2	2	1	2	S	7	O	18,000	37 0	..	10 1	3	4	..	..	Blade	A	15	..	..
18	1,550 kw	967	4.35	FP	1	...	1	...	...	...	...	...	...	...	K	..	..	..	..	2	0	..	..	None	..	..	..	..
19	1,600 hp	1300	...	O	1	...	...	...	...	...	...	...	...	...	...	..	..	..	..	2	0	..	..	..	A	15	86	..
20	5,500 hp	...	...	O	1	...	...	...	...	...	...	...	...	...	...	..	..	..	..	2	0	..	..	..	A	15	86	..
21	3,500 kw	1400	6.0	O	1	6.7	1	0	1	0	0	1	M	0	NG	1,000 <sup>a</sup>	30+	0.33	..	2	0	..	..	..	A	15	86	..
22	3,500 kw	1400	5.9	O	1	6.7	1	0	1	0	0	1	M	0	BO	17,400	17	0.33	..	2	0	..	..	..	A	15	86	..
23	5,000 kw	1500	9.0	O	2	7 2-8.7	1	2	2	2	1	1	M	75	BO	17,400	28	..	94 <sup>b</sup>	2	0	..	..	..	A	9	44	..
24	5,000 kw	1500	9.0	O	2	7 2-8.7	1	2	2	2	1	1	M	75	NG	1,000 <sup>a</sup>	28	..	72 <sup>b</sup>	2	0	..	..	..	A	9	44	..
25	2,000 hp	1350	5.0	O	1	9.2	1	0	1	0	0	1	M	0	O	..	..	0.33	14 <sup>a</sup>	0	8	86	..	No	A	20	75	84
26	12,500 kw	1250	10	C	2	3 0-8 5	2	2	4	4	3	2	S	88	GO	18,540	32 9	0.38	230 <sup>a</sup>	0	2 <sup>a</sup>	..	..	..	A	14	47	..
27	15,000 kw	1200	10	O	2	3 0-5 5	2	2	2	2	1	2	S	75	D	18,500	28 0	0.34	..	..	..	..	..	..	A	..	..	..
28	15,000 kw	1200	...	O	2	...	...	...	...	...	...	...	...	...	O	18,500	..	..	..	..	..	..	..	..	A	..	..	..
29	10,000 kw	1200	...	O	2	...	...	...	...	...	...	...	...	...	O	18,500	..	..	..	..	..	..	..	..	A	..	..	..

Table 25-4. Design Survey of Gas Turbines—(Continued)

General characteristics													Fuel		Performance			Turbines			Compressors							
No.	Name plate or rated capacity	Turbine-inlet temp, deg F	Pressure ratio	Cycle	No. shafts	Shaft speeds, rpm	No. cylinders	Cylinders in series	Compressor cylinders	Compressors in series	Intercoolers	Heating stages	Combustor type	Regenerator effective-ness, per cent	Type	Btu, net	Thermal efficiency, per cent	Work ratio	Air rate cfm/kwhr	Impulse stages	Reaction stages	Engine efficiency, per cent	Blade or disk cooling	Type	No. stages	Discharge pressure, psia	Compression efficiency, per cent	
30	4,000 kw	1000	4.0	O	1	30	1	0	1	0	0	1	S	0	BO	18,257	18T	..	....	..	..	..	88T	None	A	62	85	
31	4,000 kw	1100	..	O	1	38	1	0	1	0	0	1	S	0	NG	18	18	..	....	..	..	..	..	None	A	..	..	89
32	4,000 kw	1100	4.6	O	2	3.6	1	0	1	0	0	1	S	0	O	18,000	19.5T	..	....	..	..	..	89	None	A	..	..	..
33	10,000 kw	1100	..	O	2	..	2	0	2	0	1	2	S	0	NG	..	23.5T	..	....	..	..	..	..	None	A	..	..	..
34	10,000 kw	1100	..	O	2	..	2	0	2	0	2	2	S	?	BO	..	30.0T	..	....	..	..	..	..	None	A	..	..	..
35	1,650 kw	1100	..	O	1	..	1	0	1	0	0	1	S	?	..	..	22.0	..	....	..	..	..	..	None	A	..	..	..
36	1,200 kw	1100	..	O	2	..	1	0	1	0	0	1	S	?	BO	..	23.0	..	....	..	..	..	..	None	A	..	..	..
37	13,000 kw	1100	..	O	2	..	2	2	3	3	2	2	S	?	BO	..	30.5T	..	..	..	..	..	..	None	A	..	..	..
38	27,000 kw	1100	..	O	2	..	2	2	4	4	3	2	S	?	BO	..	34.0	0.43	40*	..	..	..	..	None	AC	..	..	..
39	12,500 kw	1250	10	CO	2	8.5-3.0	2	2	4	4	3	2	S	90	O	..	34.0	..	..	..	..	..	..	..	A	..	..	..
40	20,000 kw	1200	20	S	3	..	4	3	4	4	3	2	S	30+	O	..	..	..	..	..	..	..	..	..	A	..	..	..
41	15,000 kw	..	..	EP	..	..	..	..	..	..	..	..	..	..	BO	18,000	36	..	....	..	..	..	..	..	FP	..	..	..
42	1,250 kw	865	3.9	FP	1	90	1	0	1	0	0	1	S	60	BO	18,000	23	0.34	58*	..	..	..	..	None	A	20	70	84+
43	2,000 hp	1300	3.5	O	1	30	1	0	1	0	0	1	S	..	GO	18,000	23.0	0.34	58*	0	6	..	Disk	A	2	58	79	
44	4,100 hp	1300	5.0	O	1	5.7	1	0	1	0	0	1	C	53	C	12,000	23.0	0.31	66.8*	0	4	88	None	C	2	57	79	
45	3,750 hp	1275	3.93	O	1	6.34	1	0	1	0	0	1	S	54	O	17,000	23.5	0.29	64.2*	0	4	88	None	C	2	57	79	
46	3,750 hp	1275	3.9	O	1	6.34	1	0	1	0	0	1	M	0	O	17,400	17.0	0.33	..	2	0	..	Yes	A	15	75	84	
47	4,800 hp	400	6.0	O	1	6.7	1	0	1	0	0	1	M	0	O	..	..	0.33	14.0*	0	8	86	None	A	23	75	84	
48	2,000 hp	1350	5.0	O	1	..	1	0	1	0	0	1	M	0	O	..	..	0.35	52.5*	0	5	89	..	A	15	77	85	
49	3,500 hp	1292	5.25	O	1	7.0	1	0	1	0	0	1	M	0	GO	18,540	20.3	..	..	..	..	..	..	..	..	..	..	..
50	2,200 hp	1100	..	O	1	5.2	1	0	1	0	0	1	S	?	O	..	17.6	0.25	..	..	0	..	..	None	A	..	58	..
51	2,500 hp	1112	4.0	O	1	5.8	1	0	1	0	0	1	S	40	BO	17,400	..	..	..	..	..	..	..	..	..	..	..	..
52	4,000 hp	..	..	O	1	..	1	0	1	0	0	1	S	?	O	..	..	..	..	..	..	..	..	..	..	..	..	..
53	3,000 hp	1400	5.6	O	2	3.79-3.6	2	2	2	2	1	2	S	76	DO	18,400	32.6	0.45	34.5*	0	10	87	None	A	..	..	..	..
54	..	..	..	O	2	..	2	2	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
55	1,200 hp	1200	4.2	O	2	5.75-3.0	2	2	1	0	0	1	..	55	O	..	20.0	0.30	16.5*	0	7	86	None	L	1	40	83	
56	6,000 hp	..	..	O	2	5.6	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	24	61	82	
57	2,500 hp	1352	3.47	O	2	7.25-3.6	2	2	1	0	0	1	M	0	GO	18,540	14.0T	0.4	47.5*	..	2	0	86	Disk	A	9	51	85

Note: Numbers at left refer to same numbered turbines in Table 25-3. Symbols follow this table.

\* Power, August, 1949.

## Explanation of Symbols in Tables 25-3 and 25-4 (Continued)

**Combustor Type:**

C: Special design for burning pulverized coal  
 D: Double (two combustors in parallel)  
 M: Multiple (usually six or more combustors in parallel)  
 S: Single

**Compressor Type:**

A: Axial  
 C: Centrifugal

L: Lysholm  
 M: Mixed-flow

**Fuel Type:**

C: Pulverized coal  
 BO: Bunker C or boiler oil  
 D: Distillate  
 DO: Diesel oil

GO: Gas oil  
 K: Kerosene  
 NG: Natural gas  
 O: Oil, unspecified

**Footnotes:**

- <sup>a</sup> Stated in cfm/hp-hr  
<sup>b</sup> Stated in lb/sec at design rating  
<sup>c</sup> Stated in lb/kwhr  
<sup>d</sup> Vortex blading  
<sup>e</sup> Stated in lb/hp-hr  
<sup>f</sup> Average at 1050°F inlet temperature  
<sup>g</sup> Btu/cu ft  
<sup>h</sup> Two stages of centrifugal compression in one casing  
<sup>i</sup> Similar unit reported sold, unidentified  
<sup>j</sup> Compounded

**General Notes:**

**Temperature:** for all but free-piston plants, this may be taken as the cycle temperature. For free-piston units it is temperature of gas exhausted from compressor to inlet of output turbine.

**Pressure Ratio:** This is approximate over-all pressure ratio for cycle. Pressure ratios for individual compressors are given under Compressors.

**Shaft Speed:** Lack of space makes it impossible to identify the shafts.

**Cycle Arrangement:** By studying data on number of turbines, compressors, intercoolers, heating stages, etc., it is possible to form a good idea of cycle.

**Regenerators:** Where regenerator is used, but its effectiveness is not known, it is indicated by a question mark (?)

**Heating Value:** Heating value is net or lower value unless marked, as 18,000 Btu.

**Thermal Efficiency:** Where heating value is on lower basis, efficiency is also, and vice versa. Values are calculated unless indicated as test data, as 29.5T.

**Work Ratio:** Defined as ratio of cycle net work output to total work developed in turbine.

**Air Rate:** Amount of air entering compressor inlet per unit of cycle net output. Units as designated (see footnotes).

**Engine Efficiency:** Defined as ratio of work actually developed by turbine expanding hot gases through given pressure range to work that would be yielded by ideal adiabatic expansion.

**Compressor Efficiency:** Defined as work required for ideal adiabatic air compression through given pressure range to work actually needed for compressor.

Table 25-5. Typical Heat Balances for Three Types of Locomotives<sup>1</sup>

	Modern coal-fired steam locomotive		Coal-fired gas-turbine locomotive		Diesel-electric locomotive	
	Btu/rail hp-hr	Per cent of total	Btu/rail hp-hr	Per cent of total	Btu/rail hp-hr	Per cent of total
Useful work. ....	2,545	6.7	2,545	20.0	2,545	26.4
Exhaust. ....	19,700	51.7	9,200	72.3	3,235	33.4
Boiler losses. ....	11,950	31.3				
Cylinder radiation. ....	2,210	5.8				
Machine friction. ....	470	1.2				
Transmission losses. ....			560	4.4	560	5.8
Lubricating oil. ....			76	0.6		
Cooling water. ....					3,160	32.7
Auxiliaries. ....	1,260	3.3	344	2.7	165	1.7
Heat input, Btu/hp-hr. ....	38,135	100.0	12,725	100.0	9,665	100.0
Train thermal efficiency (18 cars, 0°F, 60 mph) per cent. ....		12.0		45.0		38.0
Cost/hr (coal 15¢, oil 50¢/million Btu).....	\$18.60		\$4.95		\$19.50	

<sup>1</sup> SILLCOX, I. K., New York Air Brake Co., "Patterns of Power," pp. 5, 6, MIT, Mar. 17, 1948.

### DUAL-FUEL INTERNAL-COMBUSTION ENGINES<sup>1</sup>

Internal-combustion engines are available which burn gaseous fuels and fuel oil. These operate on the full diesel cycle, whether on gas or fuel oil, and are immediately convertible from one fuel to the other.

The dual-fuel engine may be properly applied any place where gas is available, nor does the gas supply need to be constant and certain. In fact, this very feature enables use of the dual-fuel engine to obtain a better gas rate, as the contract may be arranged for cutoff should the gas company find it inconvenient to supply gas because of weather conditions or other factors.

The dual-fuel engine has been widely applied to municipal and industrial plants and to a lesser degree in sewage plants and on oil-field drilling rigs.

Automatic cutover from one fuel to the other is simple and practical where desired.

Figure 25-7 shows savings in dollars per year per 1,000 hp for various fuel prices for dual-fuel engines in comparison with spark-ignition gas engines and oil diesels.

Among claims made for dual-fuel engines are higher efficiency and increased power for a given size than from a straight gas engine.

### USE OF ANTHRACITE AS METALLURGICAL AND CUPOLA FUEL<sup>2</sup>

The function of fuel in an iron blast furnace is to furnish carbon monoxide for the reduction of the iron ore in the upper parts of the furnace and to provide more than enough heat, together with the heat brought in by the hot blast, to melt all the iron when reduced and to melt all the slag produced by the flux, the gangue of the ore, and the ash of the fuel. Since the fuel is the only solid of all the solid materials fed into the top of a blast furnace that reaches the tuyères, it is desired that the fuel be firm enough to withstand not only abrasion and crushing, but also the action of gases and molten slag and iron. Anthracite has this firmness to a greater degree than any other fuel. Here again, the question of resistance to thermal shock and thermal decrepitation becomes an important factor, and the research of The Pennsylvania State College is a reference. Since the loss of a major portion of this market to other fuels, many technological changes have come about and there is reason to believe that technological advances could be made which would recapture this market in the primary anthracite market area. Considerable work has been done by Brown and reported in the *Transactions of the Third and Fourth Annual Anthracite Conferences at Lehigh University*. Egg-size anthracite has been used for this work.

During the years 1854 to 1874 anthracite was in first place as a metallurgical fuel in the United States; in 1938 only 205,000 tons were so used. While there were several reasons for this virtual abandonment of the use of anthracite, it is of utmost importance that a full technical knowledge of the use of fuels in such metallurgical processes as cupolas was not gained until anthracite had ceased to be an important fuel. Present-day technicians are thus generally without personal observations on the relative advantages and disadvantages of anthracite, or on equipment manipulation that might permit its use advantageously. Sweetser<sup>3</sup> points out that "no blast-furnace man has yet used anthracite under as favorable conditions as he uses by-product coke. Until that time comes no satisfactory comparison of these two blast furnace fuels can be made." He continues by pointing out that the reactivity of anthracite lies about midway between charcoal and coke. The average reducing

<sup>1</sup> Abstracted in *Power*, March, 1949, from "Status of Dual-fuel Engine Development," SAE paper, by RALPH L. BOYER, Vice-president, The Cooper-Bessemer Co., annual meeting, Detroit, January, 1949.

<sup>2</sup> KERRICK, J. H., research engineer, The Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa., September, 1949. SWEETSER, RALPH H., Anthracite as a Metallurgical Fuel, *Trans. 2d Ann. Anthracite Conf. Lehigh Univ.*, p. 101, 1939. BROWN, J. F. K., Observations on the Use of Anthracite in Cupolas, *Trans. 3d and 4th Ann. Anthracite Conf. Lehigh Univ.*, p. 193, 1940; p. 67, 1941.

<sup>3</sup> *Op cit.*

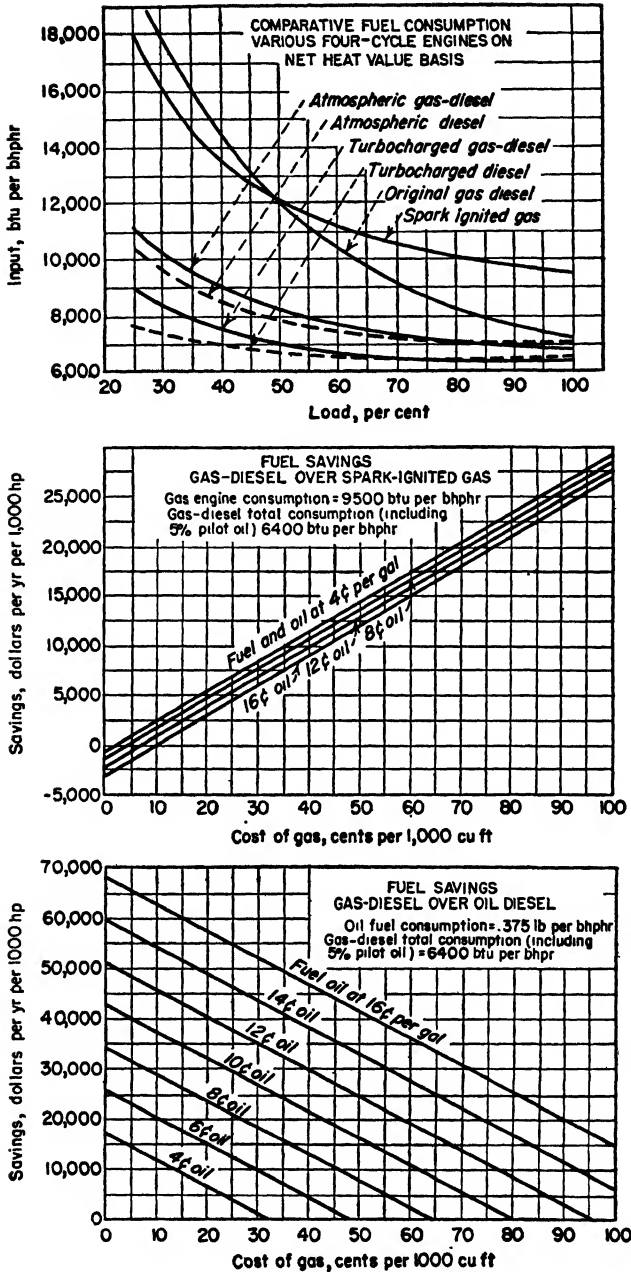


FIG. 25-7. Comparison charts show: fuel-consumption curves for various 4-cycle engines, top; fuel costs for gas-diesel vs. gas engine, center; gas-diesel vs. oil, bottom. (R. L. Boyer, SAE Paper, 1949.)

power of anthracite (amount of  $\text{CO}_2$  reduced to CO under comparable conditions) is 57 per cent, with initial reaction temperature of  $1061^\circ\text{F}$ ; the average reducing power of five coke samples under the same conditions ( $1652$  to  $1742^\circ\text{F}$ ) was 22 per cent with an initial reaction temperature of  $1319^\circ\text{F}$ .

This quality is extremely important in the consumption of blast-furnace fuels in the so-called combustion zones in front of the tuyères. In coke furnaces, such zones have been well marked and explored, but not until anthracite had ceased to attract attention as a fuel. Another advantage of anthracite is that a piece of given size contains twice as much carbon as coke.

A good blast-furnace fuel must be low in ash; (1) the more ash the less carbon; (2) the more ash the more flux is required to flux the ash which is not released until the fuel is completely gasified at the tuyères.

Brown<sup>1</sup> published comparative results between runs in a 36-in. cupola on coke and on anthracite (see Table 25-5). The following general conclusions and advantages and disadvantages were from this work.

#### Anthracite vs. Coke in Cupolas

1. Considerable improvement was obtained as experience with anthracite was acquired.

2. Observation indicates that anthracite acquires the so-called advantages of coke, porosity, change of carbon surface, and minimum of volatile.

Table 25-6. Comparison of Coke and Anthracite as a Cupola Fuel<sup>1</sup>

	Coke	Anthracite
Size of furnace, in	36	36
Number of tuyères	4	4
Size of tuyères, total sq in	144	20
Air volume, cfm	2,500	1,800
Air pressure, oz	6.8	13
Bed height, in...	36-40	20-24
Bed fuel, lb....	840	900
Charging ratio...	9.4:1	10:1
Intermediate charge, lb	160	100
Total fuel (18,000-lb heat)	2,600	2,570
Size fuel	Large and small	Egg
Metal to charge doors, lb	4,500	6,000-7,000
Time over spout, min	8	7
Time first 1,500-lb metal	21-22	23-24
Avg temp metal, deg F	2,640	2,720
Melting rate/hr.	3.2	3.0
Metal analysis:		
Total carbon, per cent	3.44	3.45
Combustion, per cent	0.69	0.80
Silicon, per cent	1.69	1.57
Sulphur, per cent	0.14	0.14
Phosphorus, per cent	0.49	0.35
Manganese, per cent	0.41	0.35
Tensile strength, psi	32,000	33,500
Transverse strength, psi	2,000	2,070

<sup>1</sup> BROWN, J. K. F., Observations on the Use of Anthracite in Cupolas, *Trans. 3d and 4th Ann. Anthracite Conf. Lehigh Univ.*, 1940, 1941.

3. With anthracite, mechanical and thermal shock take place to a small extent. Breakage aids combustion by exposing more surface.

4. Melting speed was low for this sized cupola (36 in.). Brown felt that this was a foundry problem, with neither the fuel nor the cupola at fault. Melting speed is a matter of air volume and size of fuel, but with air volume must go equal air distribution.

<sup>1</sup> *Op cit.*



5. Neglect of the effect of the two factors in anthracite, density and size, may reduce production and fail to heat the metal properly. However, when density and size are properly considered, results at least equal to coke may be expected. Quantity of fuel, air volume, and penetration of air through the coke must be readjusted for anthracite, but no material changes in design or practice are required.

6. Density means more carbon to use in less space. This can be solved by lowering the fuel-bed height, distance above the tuyère to the melting zone.

7. Small-sized coal means smaller air voids in the fuel bed. This can be solved by smaller tuyères.

8. Density and small coal together mean slow first taps. This was solved by shutting the charging door.

#### **Advantages of Anthracite.**

1. 7,000 lb metal per charge in the cupola tested (36 in.) as compared with 4,500 lb coke. Charging labor is saved.

2. Clean metal without using fluxes, up to 20,000 lb cast, owing to high melting point of anthracite ash. Saves limestone.

3. Minor constituents in anthracite ash improve quality of metal. Sulphur, for example, in anthracite can be partly volatilized; in coke it is fixed.

4. Metal has the quality of retaining its heat. This was an advantage previously claimed for anthracite metal when anthracite was the leading fuel. Results in low loss of castings from cold pouring. Brown reported only 3,000 lb lost out of 1,750,000.

5. Higher melting ratios with anthracite than 10:1 seem possible; coke experts advocate 8:1.

6. First taps are always hot and useful. Many foundries throw away half of their first metal as too cold.

#### **Difficulties and Disadvantages of Anthracite.**

1. These are almost entirely ones of the distribution of air due to small-sized fuel. This is the same problem that faces blast-furnace operation, boiler plants, etc., where the difficulties of placing the air at the right place, at the right quantity, at the right time are paramount. Experimentation should furnish the solution, as by:

a. Determining the factors and principles that govern air distribution for various sized coals and various sized cupolas.

b. Using larger sized coal with greater voids.

c. Using a clearing flux more liquid than limestone, which would keep the voids more open.

**Air Required for Blast Furnaces.** In the blast-furnace industry it is common to assume that anthracite requires three and a half times the quantity, velocity, and density or compression of a blast necessary and proper for charcoal and that coke requires two and a half times as much as charcoal. Sweetser<sup>1</sup> feels that this is highly erroneous and points to the fact that it was originally derived from a patent filed by Geissenhainer for the application of anthracite coal as long ago as 1883.

In Sweetser's own experience, in the same blast furnace, smelting the same ores, to make the same kind of Bessemer pig iron, and using the same blowing engines, it took 1.44 times as much air blast by volume to burn 1 lb beehive coke as to burn 1 lb charcoal.<sup>2</sup> Kreisinger<sup>3</sup> found that anthracite required only 95.6 per cent as much air for combustion as coke. In practice Sweetser found that it requires approximately the same volume of air to burn anthracite as to burn coke in the same blast furnace.

<sup>1</sup> SWEETSER, RALPH, H., "Blast Furnace Practice," pp. 146-147, McGraw-Hill Book Company, Inc., New York, 1938.

<sup>2</sup> *Trans. AIME*, vol. 39, p. 228, 1909.

<sup>3</sup> *U.S. Bur. Mines Tech. Paper* 137, p. 54.

**PENNSYLVANIA ANTHRACITE (ANTHRAFILT) AS A FILTER MEDIUM<sup>1</sup>**

Since Pennsylvania anthracite is essentially a carbon and hence more nearly chemically inert than other substances used in filters, it is well suited for many filtration processes. Its conchoidal fracture produces a particle which has the most desirable shape for filter use; its low specific gravity and angular particle shape make possible longer filter runs and more effective filter-bed washing at lower backwash rates. Filter capacities have been increased from 25 to 100 per cent through the use of anthracite as a filter medium.

Pennsylvania anthracite is used in municipal filters, power-plant filters for the hot-process softening of waters and for oil removal from boiler condensates, swimming-pool filters, filters for clarification of chemicals, and sewage filters.

In the preparation of *Anthrafil*,<sup>2</sup> care is given to the selection of a low-ash material with the optimum particle shape; the most important single factor involved is the manufacture of the correct particle size to meet the conditions of filter use and design.

**Preparation of Anthracite.** Since all Pennsylvania anthracites are not equally well suited for use in filters and since quality, particle shape, and particle size are critical factors in all anthracites that are suitable, the term "Anthrafil" has been used to designate Pennsylvania anthracite that meets all requirements for successful use in filters.

The first step is the selection of a coal that will yield a particle free from small fracture cracks and possessing the best shape. The particle must be strong enough to withstand years of backwashing without breaking into smaller grains; its shape should be longer than it is wide but should not be extremely thin.

This anthracite must be cleaned to a low ash product, and to the desired particle size. It has been found that three fine sizes fit most cases.

**Properties of Anthracite and Sand.** Silica sand is the prevailing filter medium in industrial and municipal water filters. It is composed almost entirely of  $\text{SiO}_2$ . It is insoluble in most acids but reacts readily with alkalis. The particle shape is usually rounded. It weighs approximately 100 lb per cu ft.

Aside from mineral matter associated with it, anthracite is essentially a carbon and hence is neutral in its behavior with acids and alkalis. The mineral matter associated with anthracite is composed of about 60 per cent silica, the remainder being oxides of aluminum with minor amounts of magnesium, calcium, and iron. The particle shape is sharp, angular, and flat. It weighs about 50 lb per cu ft.

The particle charge on silicas is negative, and so likewise is the particle charge on crushed anthracite. The charge on silica sand is weak, however, compared with the strong charge on anthracite.

In the removal of solids from liquids by drainage beds, filters act as entrapping agents rather than as strainers. The water or other liquid is usually treated with a coagulant which agglomerates the solid particles, many of which are so small that they would pass through an ordinary filter. Since the degree of entrapment is directly proportional to the surface exposure of the filter medium, the sharp angular particle of *Anthrafil* is more efficient than the same size sand having a spherical shape. In practice it has been found that *Anthrafil* having an effective size of 0.70 mm and a uniformity coefficient of less than 1.60 removes the same amount of solids as does a rounded silica sand with an effective size of 0.45 mm and a uniformity coefficient of 1.60.

For many years the average sand size used in filters has been one with an effective size of 0.45 mm and a uniformity coefficient of less than 1.60. Recently, however,

<sup>1</sup> TURNER, H. G., *Ind. Eng. Chem.*, vol. 35, p. 145, February, 1943.

<sup>2</sup> Trade-marked name for anthracite specially prepared as a filtration medium, Anthracite Equipment Corp., Wilkes Barre, Pa.

there has been a trend toward a coarser particle size. One of the limiting factors has been that most filters are not designed with a wash-water velocity high enough to produce the necessary degree of bed expansion when the filter is backwashed.

Hulbert<sup>1</sup> showed that 50 per cent expansion of a filter bed is desirable for effective washing of a filter. Because of the light weight of *Anthrafilt*, a 50 per cent expansion is possible without increasing backwash velocities, even when the particle is considerably coarser.

As compared with a fine filter medium, a coarse one will give longer runs between backwash periods, will not clog so readily with fibrous turbid matter, will release the dirt on grains with greater ease when backwashed, will have less head loss through the filters, and will permit higher filtration rates.

Since *Anthrafilt* of coarse size is as efficient in turbid-matter removal as finer sand and weighs half as much, it can obviously be substituted for fine sand without detracting from a high degree of bed expansion under the same backwash velocity as used with fine sand.

Because of the carbon composition of *Anthrafilt*, it does not react chemically with the turbid matter which envelops the grains during filtrations; hence the filter particles are more readily cleaned under routine backwashing, and with proper filter design the particles will never coat with salts such as those of lime, iron, and manganese. Sand, on the other hand, often coats so badly that it has to be discarded because of filter-bed cementation or because the sand particle becomes so heavy that it can no longer be lifted by the backwash water.

Where water is treated with lime in cold-process softening, silica sand becomes badly coated with layers of lime that cannot be removed by mechanical means because of the chemical reaction between the acid silica and the alkaline lime.

Where hot-soda process softening is used, as in boiler-water treatment, the hot alkaline waters dissolve the silica sand and impart a silica scale to boiler tubes which is difficult to remove. A small amount of silica is leached out of *Anthrafilt*<sup>2</sup> under these conditions, but after the first few days of operation the effluent is practically free of silica. Mercerizing plants have also found *Anthrafilt* advantageous in the filtration of caustic soda. It can be seen also that *Anthrafilt* is advantageous in the filtration of many chemicals which would react with other filter mediums.

Swimming-pool filters have used *Anthrafilt* with marked improvement over sand. The turbid matter of swimming pool filters is largely fibrous, being composed chiefly of lint and hair. This kind of turbid matter clogs fine sand in a few hours but does not clog coarse *Anthrafilt*. Furthermore, swimming pool filters are usually provided with a low wash-water velocity which is not very effective with the relatively heavy silica sand.

Lake waters are commonly infested with algae during spring and autumn. At such times, *Anthrafilt* filters still give long runs,<sup>3</sup> whereas runs through sand are so short as to be serious in the reduction of plant capacity.

In the removal of emulsified oil and turbidity from boiler-feed condensate, *Anthrafilt* has been found very effective. Coagulants such as alum, ferric sulphate, or ferrous sulphate are added and produce spongy gelatinous masses which are easily removed without clogging the coarse *Anthrafilt* filter bed.

In the removal of iron and manganese salts from municipal water supplies, *Anthrafilt* has been more effective<sup>4</sup> than sand in spite of the fact that, it is commonly believed, a sand must be coated with iron or manganese oxides to be effective; *Anthrafilt* apparently does not coat.

<sup>1</sup> HULBERT, ROBERTS, J. *Am. Water Works Assoc.*, vol. 34, p. 1045, July, 1942.

<sup>2</sup> TURNER, H. G., and G. S. SCOTT, *Combustion*, vol. 5, No. 11, p. 23, 1934.

<sup>3</sup> PALMER, C. E., *J. Penna. Water Works Operators' Assoc.*, vol. 11, p. 91, 1939.

<sup>4</sup> COOK, A. T., *Water Works Eng.*, September, 1933.

Combination *Anthrafill* and sand beds are feasible only where the filter is provided with agitation devices to be used during backwashing. It has been found that a layer of the turbid matter forms at the junction of the sand and *Anthrafill*, and this can be removed only by agitation during backwashing.

Where sand combinations are used, the total filter-bed depth should be made up 50 to 66 per cent *Anthrafill* for best results.

### FIRING CERAMIC PRODUCTS<sup>1</sup>

**Types of Kilns.** Kilns for heating clay ceramics to temperatures of maturity are divided into general types of periodic and continuous. In the periodic the relative position of fires and ware is stationary, and firing is periodic and not usually regenerate; of the continuous kilns, the fires are movable and the ware is stationary in the so-called continuous type, while in the tunnel type the fires are stationary and the ware is movable. In both the firing is continuous and stored heat is utilized. Muffles are used to shield some wares from contact with the products of combustion.

**Variation in Clays.** The clays used vary considerably in characteristics; some are susceptible to damage by slight variations of the atmosphere in the kiln, whereas others are not affected deleteriously by large changes of atmosphere. This applies notably to the oxidizing or reducing character of the gas that enters the kiln, sulphur and chlorides in the gas, and particles of ash and combustible borne by the gas.

**General Fuel Requirements.** Basically the following applies in the selection of a fuel for kilns: (1) Substances that can harm the ware by direct contact must be absent; such substances are constituents of the ash, sulphur, and chlorides. (2) Properties that facilitate exact control of the operation of kilns are desirable; such properties include those which permit fuel beds of low resistance so as to minimize desirably differences in pressure throughout the kiln. (3) High rates of heat release should be possible. (4) Properties that reduce the labor of firing are desirable. (5) There may be other requirements for the fuel, depending upon local conditions.

**Selection of a Coal.** Where coal is selected as the fuel, the following are desirable: The coal should be free-burning. A desirable size is usually 2 by 4 in.; in suitable furnaces, a size as small as 2 by 1 in. may be preferable. As the coal is more strongly caking the size becomes of less importance. Impurities are always undesirable, especially for the higher quality wares. Moisture content should be low. An arbitrary maximum might be about 5 per cent; high moisture is particularly undesirable in the firing of higher grade products susceptible to damage by reducing atmosphere, when, by water-gas reactions, it increases the likelihood of reducing gases entering the kiln. The least possible ash is desirable. Softening temperature of ash should preferably be not less than 2600°F; the importance of this factor increases as the maturing temperature of the ware is higher. High-volatile is preferable except where the ware might be damaged by smoke or reducing atmosphere. The importance of sulphur increases as the grade of the ware is higher; for highest grade white wares, sulphur content of 1 per cent or less is desirable. Sulphur is less troublesome for products in the heavy clays groups, particularly if the ware is thoroughly dried before being placed in the kilns; 3 per cent is often acceptable in such cases.

### MANUFACTURE OF CARBON DIOXIDE

Carbon dioxide is manufactured and collected commercially for many purposes such as dry ice, liquid carbonic gas, and basic carbonate of lead. Several methods of manufacture are in effect, such as from burning lime, as a by-product of distilleries, and from gas wells which do not involve the basic use of fuel. However, in many instances, fuel, preferably anthracite or coke, is burned in conventional furnaces and

<sup>1</sup> Rice, W. E., National Association of Purchasing Agents, *Bull.* 10.

the flue gas is collected, scrubbed, and otherwise prepared as needed. Virtually the only change in equipment over that required for straight combustion is to allow very ample furnace volume and relatively long gas travel.

Coke is usually used in the dry-ice industry, although as no record can be found of either the extensive use or reliable test of anthracite, it can only be concluded that this is largely due to the impetus of early habits and economics. This is supported by Turnbull,<sup>1</sup> who describes a preference for anthracite necessarily clean, pure CO<sub>2</sub> for the basic-carbonate white-lead process as because of "its high carbon content, low volatile, and low sulphur," together with uniform supply and uniform controllable combustion results.

**Reduction of H<sub>2</sub>S.** Aside from a selection of as low a sulphur coal as can be obtained, Turnbull, after extensive experimentation, found that the most practical way to reduce the formation of the highly objectionable H<sub>2</sub>S is to restrict materially the size of the draft openings in the ashpit to the point where there is a very definite negative pressure under the grate. He reports that, while this did not entirely eliminate the production of H<sub>2</sub>S, it certainly lessens it.

**Operation of Equipment.** With traveling-grate stokers and rice anthracite, and where the production of steam can be considered as secondary, a continuous production of gas of better than 14 to 15 per cent CO<sub>2</sub> can be expected. When operated properly, there should be no sulphur in the form of H<sub>2</sub>S. In the latter connection, it was noted that, when such a stoker is operated with a slight positive overfire-air pressure, very appreciable quantities of H<sub>2</sub>S are formed; the H<sub>2</sub>S disappeared immediately from the gas when the draft balance was changed so that there was a negative overfire-air pressure.

Hand-firing of the egg and other upper sizes of anthracite and coke should yield gas having a CO<sub>2</sub> content up to 17 to 19 per cent. Necessary periodic interruptions to fire coal temporarily reduce the CO<sub>2</sub> and thus are disadvantageous. From this angle, anthracite should be preferable, since its bulk permits a reduction of the firings necessary to about one-half of those with coke.

<sup>1</sup> TURNBULL, E. D., Experience in Using Anthracite in the Manufacture of Basic Carbonate White Lead, *Trans. 4th Ann. Anthracite Conf. Lehigh Univ.*, p. 29, 1941.

## **SECTION 8**

### **GENERAL**



## CHAPTER 26

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### BOILER MEASUREMENTS AND TESTS

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## GENERAL USE OF COMBUSTION INSTRUMENTS<sup>1</sup>

Instruments are of vital importance for proper furnace operation as they form a means for ascertaining the conditions under which the plant is operating.

An **overfire-draft gauge** indicates the intensity of furnace draft as a guide to fly-ash elimination and rapidity of gas travel. It is an indicator of the losses due to infiltration through the brickwork, as these increase with draft increases.

An **undergrate or fan-pressure indicator** is a guide to fuel-bed conditions. By indicating rising pressure, it warns of a caking, coking, or clinkering fuel bed or an unbalanced fuel-air ratio. By indicating falling pressure, it warns that a fuel bed is burning out or becoming too thin. An abnormal drop in pressure indicates formation of blowholes.

A **flue-gas-temperature indicator**, in conjunction with a **carbon dioxide indicator**, furnishes a check on over-all efficiency and detects losses due to sooting of heating surfaces and excessive draft. It also serves as a close check on fuel-air ratios.

A **carbon monoxide indicator** points to incomplete combustion. It is of particular value when smokeless fuels, such as anthracite and coke, are being burned, as there are usually no other such signs of inadequate air.

## FLUE-GAS ANALYSIS

### Sampling

A sampling tube can be made from  $\frac{1}{4}$ -in. pipe, so placed as to secure an average sample of the flue gas. If only a single test point is required, the sample can be taken from the exit gas before the outlet damper.

The gas composition may not be homogeneous because of stratification; consequently if more accurate results are desired a traverse of the gas passage is made. This is done by dividing the cross section into equal areas and taking a sample from the center of each.

The ASME Test Code<sup>2</sup> states that the best practical method of obtaining a true sample is to divide the cross section of the gas passage into equal areas and to take velocity measurements and gas samples from the centers of these component areas. A weighted average can then be calculated, taking into account the gas temperature as well as the velocity. The number and arrangement of the equal areas will depend on the size and layout of the gas passage, although it is recommended that the individual areas be not greater than 18 sq ft.

The location of test points in a **circular duct** can be readily accomplished by the use of Table 26-1.<sup>3</sup>

**Table 26-1. Layout Measurement for Circular-duct Traverse**

No. of equal areas	Total No. of readings	Distances from center of pipe to point of reading in fraction of pipe diam					
3	12	0.204	0.353	0.455			
4	16	0.177	0.305	0.394	0.466		
5	20	0.155	0.272	0.353	0.417	0.474	
6	25	0.145	0.250	0.323	0.382	0.433	0.479

<sup>1</sup> "Smoke," p. 6, The Perfex Corp., Milwaukee, 1947.

<sup>2</sup> ASME Test Code for Stationary Steam-generating Units, p. 18, ASME, New York, 1946.

<sup>3</sup> Tove, G. L., in "Mechanical Engineers' Handbook," edited by LIONEL S. MARKS, 4th ed., p. 2102, McGraw-Hill Book Company, Inc., New York, 1941.

Figure 26-1 illustrates a circular duct laid out in three equal areas, with the test points located from data taken from Table 26-1. Readings are taken along two diameters placed 90 deg apart, which will tend to average differences in velocity and analysis in the duct.

**Time of Sampling.** When the apparatus has reached equilibrium, the sample is drawn. Samples should not be taken when the furnace doors are open or when the soot blowers are in operation or when fuel is being fired, if hand-operated.

**Sample Containers.**<sup>1</sup> A convenient and frequently used method of sampling (Fig. 26-2) is to fill the sample container with leveling-bottle liquid and to permit the discharging fluid to pull a gas sample into the container. When filled, the device may be taken directly to the gas apparatus and the sample discharged into the burette without disconnecting the tube from the leveling bulb. The container shown is made of glass, but more sturdy copper or zinc tubes are available. However, the metal stopcocks are more apt to develop leaks than are glass stopcocks.

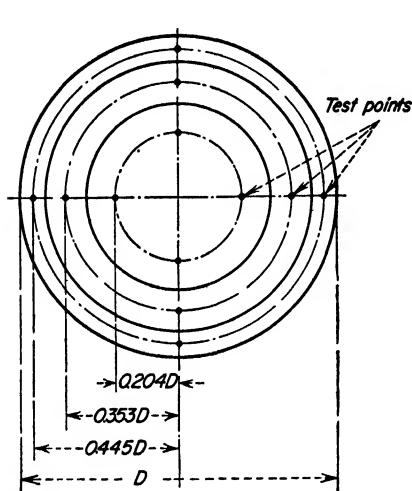


FIG. 26-1. Circular duct divided into three equal areas, showing test points.

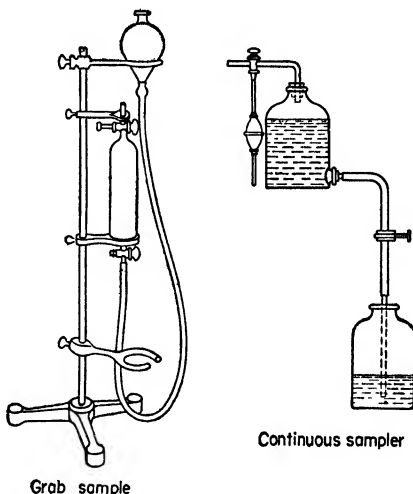


FIG. 26-2. Gas-collection apparatus: grab sample and continuous sampler. (Burrell Corp.)

**Direct Sampling.** At times, it is possible to place the apparatus close to the point of sampling and to draw or force the sample directly into the burette and proceed at once with the analysis. Avoid areas where large temperature changes might occur which may affect the volumes in the apparatus. If the gas is under pressure, it is easy to permit a sufficient volume to flow through the sampling line to displace all the air. If the sample must be pulled into the burette by lowering the leveling bottle or by forcing into the burette by means of a rubber hand pump, a 100-cc burette should be filled and discharged at least twice for every 5 ft of  $\frac{1}{4}$ -in. inside diameter sampling line to clear the line of air or residue gas.

A convenient device to take a **continuous sample** is an aspirator, usually water-operated. A tee is placed ahead of the aspirator, and the Orsat apparatus is connected to the tee. Analysis is made as desired.

Another continuous sampler is shown in Fig. 26-2. With this, a large sample or a sample collected over a long period of time may be gathered. If the gas is under pressure, the line is flushed out through the tee or tail stopcock. If not under pres-

<sup>1</sup> "Burrell Manual for Gas Analysts," Catalogue 80, pp. 59-76, Burrell Corp., Pittsburgh, Pa.

sure, the line can be flushed by means of the rubber hand pump. The stopcock is turned to permit the sample to pass into the bottle. The rate of sampling may be regulated by adjusting the screw clamp in the liquid-discharge connection.

### Gas-analysis Apparatus

The Orsat apparatus is illustrated diagrammatically in Fig. 26-3. This instrument is fairly reliable when used in testing and operational checks.

The burette, usually of 100 cc capacity, is water-jacketed to protect it from sudden changes of temperatures.

The leveling bottle acts as a pump to force the gas into the apparatus, and then to the respective pipettes as required.

The pipettes, of which there are three in the standard Orsat (some have only one pipette for the absorption of  $\text{CO}_2$ ), contain reagents for the absorption of  $\text{CO}_2$ ,  $\text{O}_2$ , and  $\text{CO}$ .

#### Absorbing Reagents.<sup>1</sup>

1. **Potassium hydroxide**, for absorption of carbon dioxide,  $\text{CO}_2$ . Strength of solution 40 per cent, by weight. (For all practical purposes this can be prepared by adding slowly 11 oz potassium hydroxide sticks or pellets to a pint (approximately 16 oz) of water. As this is accomplished by the emission of considerable heat, this mixing should be done in a pyrex container. Allow to cool before using.) One cubic centimeter absorbs 40 cc of carbon dioxide.

This reagent will also absorb any other acid gas such as sulphur dioxide or hydrogen sulphide in addition to carbon dioxide.

2. **Potassium pyrogallate** for the absorption of oxygen,  $\text{O}_2$ . Equal volumes of 33 per cent by weight of potassium hydroxide and 25 per cent by weight of pyrogallic acid solutions are mixed together. One cubic centimeter will absorb 8 cc of oxygen.

Carbon monoxide may be given off by the reagent if high concentrations of oxygen are absorbed.

3. **Cuprous chloride** for the absorption of carbon monoxide,  $\text{CO}$ . A solution of cuprous chloride is prepared by dissolving  $\text{Cu}_2\text{Cl}_2$ , cuprous chloride, in hydrochloric acid (specific gravity 1.12) in the ratio of 15 g salt to 100 cc acid. The activity of the solution depends on the presence of copper in the cuprous form. If pure, the solution would be colorless. It turns green upon oxidation. It should be kept from light and occasional additions of copper wire or turnings made to the accessory pipette or stock bottle.

The solution in the Orsat should be kept fresh, since there is evidence that the reagent, even after only moderate use, will give off carbon monoxide when in contact with a gas containing carbon monoxide in small amounts.

4. **Leveling-bottle fluid.** A precaution should be taken to see that the water in the burette is saturated with the gases to be analyzed; else some absorption will take place and low results will be obtained. For this reason, it is usually advisable to aspirate the gas through the burette and leveling bottle before collecting a sample. Slightly acidulated water should be used. The presence of a few drops of methyl orange can be used to detect any contamination resulting from accidentally drawing alkaline liquid from the pipettes into the burette, and also to make the meniscus clearly visible.

### Use of Orsat Apparatus

**Preparation.** If the Orsat has not been in use for some time, renew all the rubber connections. Clean the stopcocks, and give them a very light touch of stopcock

<sup>1</sup> PARR, S. W., "The Analysis of Fuel, Gas, Water and Lubricants," 4th ed., pp. 301-304, McGraw-Hill Book Company, Inc., New York, 1932.

grease. Fill the pipettes and the leveling bottle. Test for leaks by drawing in 100 cc of air and close the three-way cock (the pipette stopcocks are left closed). Raise the leveling bottle and place it on top of the Orsat. If the liquid level rises, there is a leak.

**Analysis.** Raise the liquid level in each of the pipettes so that it is just below the stopcock. Open the three-way cock and raise the leveling bottle so that all the air is discharged. Turn the three-way cock so that the Orsat is connected to the gas-sampling tube. Lower the bottle and draw in a sample. Discharge this sample through the three-way cock by raising the bottle. Repeat this three or four times to ensure that the lines and the apparatus are purged of air.

Draw in final sample so that the liquid level is at the lowest division and the level in the bottle matches it, as shown in Fig. 26-3. The gas is at atmospheric pressure.

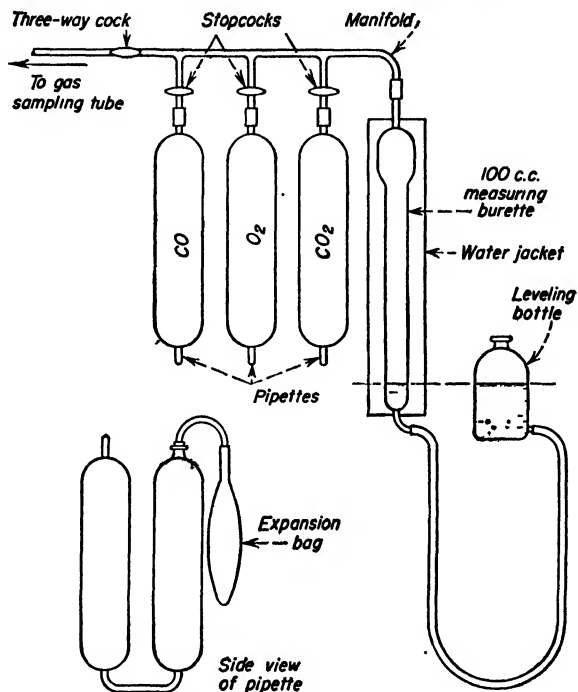


FIG. 26-3. Orsat apparatus.

Close off the three-way cock. Open the cock to the CO<sub>2</sub> pipette and pass the gas through several times by raising and lowering the bottle. Take a reading, ensuring that the level in the burette and in the leveling bottle is the same. Repeat this procedure until there is no change in level between successive readings, indicating complete absorption. Follow the same procedure for the other two pipettes, noting the readings after the gas is completely absorbed. Direct readings are obtained since the burette is graduated in hundreds. Nitrogen =  $100 - (\text{CO}_2 + \text{O}_2 + \text{CO})$ .

The absorption procedure must follow the order CO<sub>2</sub>, O<sub>2</sub>, and CO, since some of the reagents can absorb several of the flue-gas components (see Reagents). Allow more passes for the absorption of the oxygen.

If the reagent is accidentally drawn, during the test, into the manifold, the pink-colored water solution will turn yellow. Dissassemble the apparatus and clean out all the affected parts.

**Storage of Orsat.** If the unit is to be idle overnight, drop the levels in the pipettes so that there is no chance that the reagents will get into the stopcocks, which may cause them to freeze.

If the unit is not going to be used for some time, it is advisable to clean it thoroughly after draining the pipettes and the leveling bottle. Clean the stopcocks, regrease

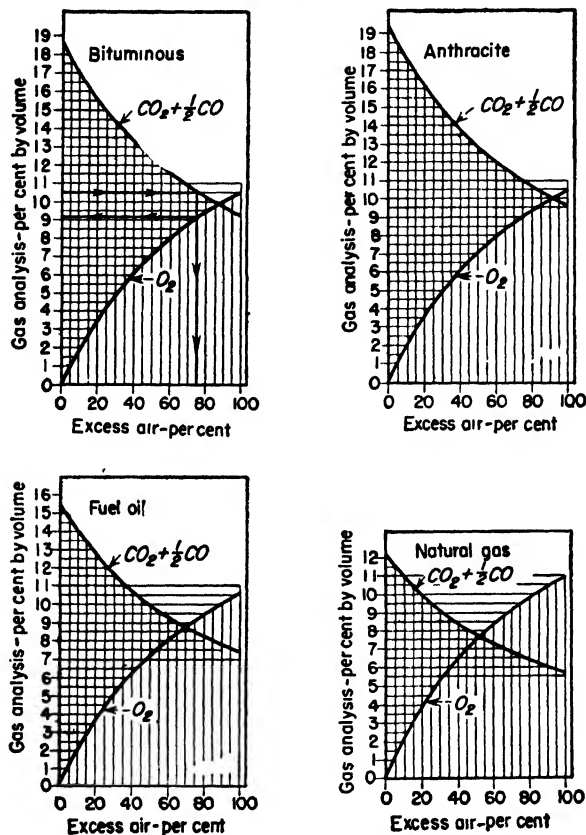


FIG. 26-4. Check chart for Orsat analysis and percentage excess air. Example of use of charts: Given an Orsat analysis 10.2 per cent  $\text{CO}_2$ , 0.6 per cent  $\text{CO}$ , and 9.2 per cent  $\text{O}_2$ ; kind of fuel—bituminous. To use: On bituminous chart enter  $\text{CO}_2 + \frac{1}{2}\text{CO} = 10.2 + .3 = 10.5$ , proceed to right to intersect  $\text{CO}_2 + \frac{1}{2}\text{CO}$ . Proceed downward to  $\text{O}_2$  line and proceed to left to find  $\text{O}_2$  reading of 9.2 per cent, which indicates the Orsat analysis is correct. By proceeding vertically downward from intersection of  $\text{CO}_2 + \frac{1}{2}\text{CO}$  the excess air = 75 per cent.) (*Power*.)

them, and insert the plugs with a piece of paper wrapped around them. An Orsat stored for any length of time with the reagents in place will usually give trouble with frozen stopcocks.

**Check of Orsat Analysis.**<sup>1</sup> After the analysis has been made with the Orsat apparatus, the analysis can be checked for accuracy by the use of the charts of Fig. 26-4. Enter at left with  $\text{CO}_2 + \frac{1}{2}\text{CO}$  (or with  $\text{CO}_2$  alone, if  $\text{CO}$  is not known and is probably negligible). Move right to curve marked  $\text{CO}_2 + \frac{1}{2}\text{CO}$  and then verti-

<sup>1</sup> SWAIN, P. W., and L. N. ROWLEY, "Library of Power Plant Engineering," Part II, Chap. 7, p. 2, McGraw-Hill Publishing Company, Inc., New York, 1949.

cally downward to curve marked  $O_2$  and then horizontally to the left. The corresponding reading of  $O_2$  on the left scale should be nearly the same as the  $O_2$  shown by the analysis. Otherwise suspect error in analysis and take steps to remedy before proceeding with further analysis.

The amount of **excess air percentage** can also be read from these charts. From intersection of horizontal line from left scale and  $CO_2 + \frac{1}{2}CO$  line, proceed vertically downward to bottom line and read excess air per cent.

**Calculation of Excess Air Per Cent from Orsat Analysis.** The excess air per cent can be determined from the Orsat analysis by the following expression:<sup>1</sup>

$$\text{Excess air per cent} = \frac{O_2 - \frac{1}{2}CO}{0.264N_2 - (O_2 - \frac{1}{2}CO)}$$

### MEASUREMENT OF FURNACE TEMPERATURE<sup>2</sup>

Research work, both in the laboratory and in the field, has shown the great importance of the method used to measure the gas temperature leaving the furnace in making a reliable evaluation of any furnace design.

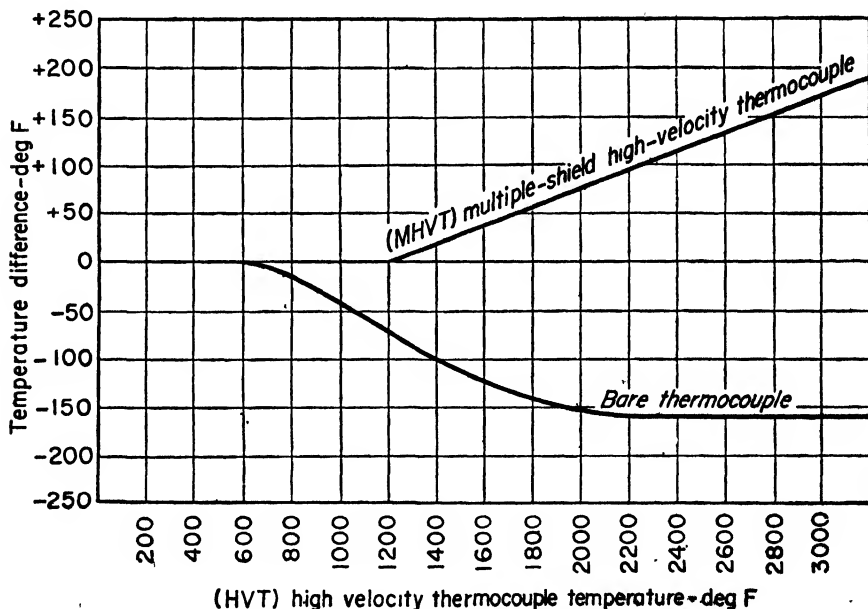


FIG. 26-5. Comparison of various methods of temperature reading. (*The Babcock & Wilcox Bull.* 3-407.)

Figure 26-5 shows the difference between the gas temperature measured by a bare thermocouple as compared with the temperature measured by a porcelain-shield thermocouple (high-velocity thermocouple—HVT) over which gas is aspirated at high velocity. These temperatures are compared with the true gas temperature, which is approached by the multiple-shield high-velocity thermocouple (MHVT). At 2000°F, it is seen that the bare thermocouple will read about 150°F lower than the HVT and about 225°F lower than the MHVT. The HVT is used for test work

<sup>1</sup> GAFFERT, G. A., "Steam Power Stations," 3d ed., p. 187, McGraw-Hill Book Company, Inc., New York, 1946.

<sup>2</sup> ROWAND, W. H., Recent Boiler Design Practice, presented at West Virginia Section ASME, 1947, Bull. 3-407, The Babcock & Wilcox Co., New York, 1947.

because of its relative ruggedness, but its readings are corrected to MHVT temperature basis for use in evaluation and design.

Figure 26-6 shows the contour plot of high-velocity thermocouple gas temperatures obtained during a test on the 800,000 lb per hr unit installed at the Springdale Power Plant of the West Penn Power Co., near Pittsburgh. These data were obtained during a test of this unit at 780,000 lb steam per hr. The input was 74,000 Btu/hr/sq ft of flat projected furnace surface. The oxidizing initial deformation temperature averaged about 2400°F. The gas temperature entering the boiler screen (corrected to a MHVT basis) averaged 2200°F and the gas temperature entering the superheater, on the same basis, averaged about 1950°F.

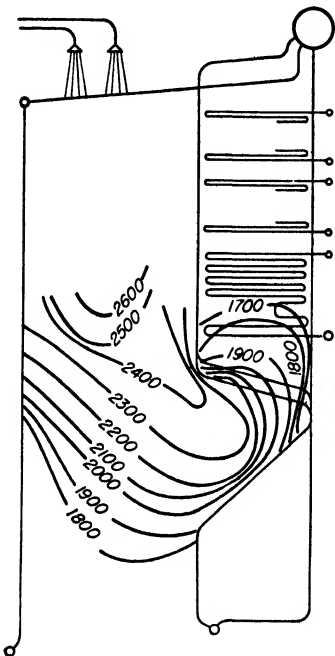


FIG. 26-6. Furnace-temperature contour plot. (*The Babcock & Wilcox Bull.* 3-407.)

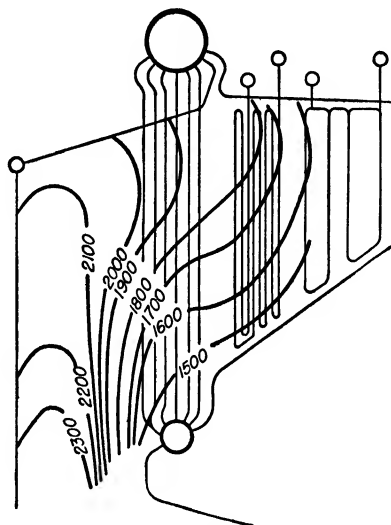


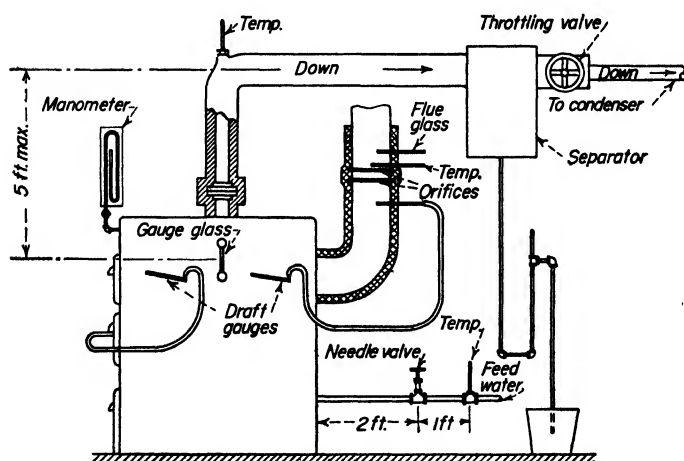
FIG. 26-7. Furnace-temperature contour plot. (*The Babcock & Wilcox Bull.* 3-407.)

Figure 26-7 shows a contour plot of high-velocity thermocouple gas temperatures obtained during a test on the steam-generating plant installed at the High Bridge Power Plant of the Northern States Power Co., which burns Illinois coal. These data were obtained during a test of the unit at 522,000 lb steam per hr. The input was 84,500 Btu/hr/sq ft of flat projected furnace surface, and the oxidizing initial deformation temperature of the ash averaged about 2350°F.

**Temperature Measurement by Refractory Cones.** A common method of obtaining approximate temperature readings in the higher temperature range is through the use of cones designed to soften at definite fixed temperatures. The most commonly used cones of this type are the Seger, the softening temperatures of which are shown as Table 26-2. A second series is the Orton cone. The temperatures as shown hold good only under very definite conditions of heating rate and furnace atmosphere; *i.e.*, if the heating rate is slow or if the cones are subjected to soaking at a steady temperature, the cones can be expected to fall at temperatures lower than those specified. Such measurements should thus be considered as only crude approximations; nevertheless, they are easy and quick and frequently suffice, especially where more elaborate instruments are not available.

Table 26-2. Approximate Softening Point of Seger Cones

Cone No.	Softening temp		Cone No.	Softening temp	
	Deg C	Deg F		Deg C	Deg F
022	600	1112	9	1280	2336
021	650	1202	10	1300	2372
020	670	1238	11	1320	2408
019	690	1274	12	1350	2462
018	710	1310	13	1380	2516
017	730	1346	14	1410	2570
016	750	1382	15	1435	2615
015	790	1454	16	1460	2660
014	815	1499	17	1480	2696
013	835	1535	18	1500	2732
012	855	1571	19	1520	2768
011	880	1616	20	1530	2786
010	900	1652	26	1580	2876
09	920	1688	27	1610	2930
08	940	1724	28	1630	2966
07	960	1760	29	1650	3002
06	980	1796	30	1670	3038
05	1000	1832	31	1690	3074
04	1020	1868	32	1710	3110
03	1040	1904	33	1730	3146
02	1060	1940	34	1750	3182
01	1080	1976	35	1770	3218
1	1100	2012	36	1790	3254
2	1120	2048	37	1825	3317
3	1140	2084	38	1850	3362
4	1160	2120	39	1880	3416
5	1180	2156	40	1920	3488
6	1200	2192	41	1960	3560
7	1230	2246	42	2000*	3632
8	1250	2282			

FIG. 26-8. Typical setup for oil-fired steel boiler test. (*Steel Boiler Institute Rating Code, 5th ed.*)



### MEASURING DRAFT

**Type and Location of Connections.** The connections to measure draft can be readily made from small bore tube or pipe. Care must be taken that the pipe and fittings are free of leaks, and that the layout is such that they are readily accessible for cleaning and drainage. Construction and location of the measuring and should be such that there is no chance of error due to impact of the moving gas stream.

*Note: Where auxiliaries are separated by damper, as between forced-draft fan and air heater, one draft measurement will not do double duty; separate measurements are needed.*

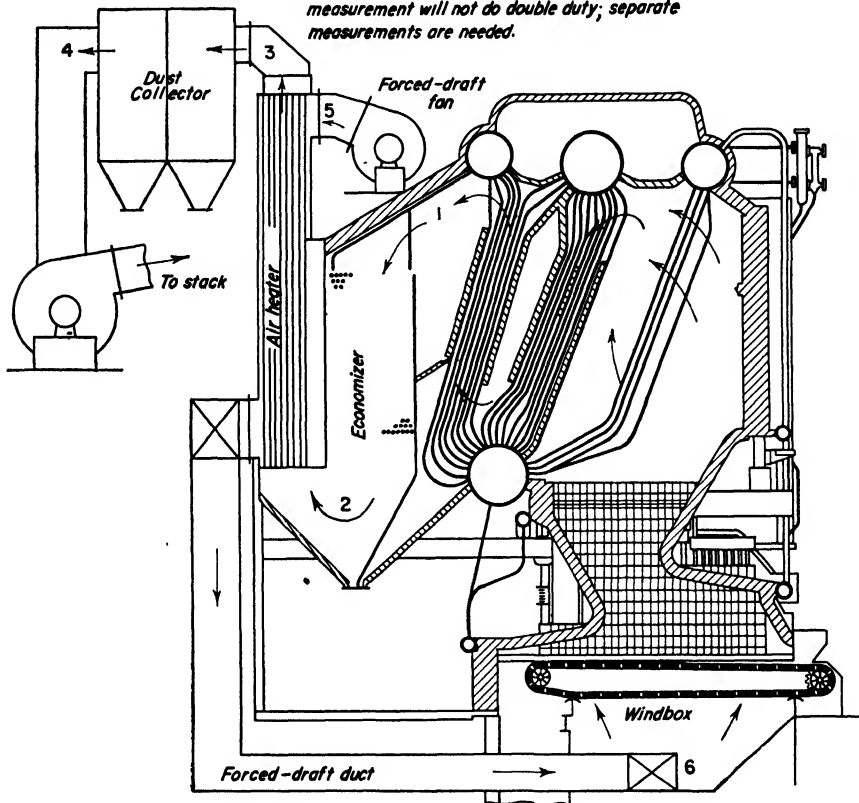


FIG. 26-9. Operating draft measurements for boiler auxiliaries. (1) Draft measurement at this point gives boiler outlet draft and economizer inlet draft. (2) Draft measurement at this point gives economizer outlet draft and air-heater inlet draft. (3) Draft measurement at this point gives air-heater outlet draft and dust-collector inlet draft. (4) Draft measurement at this point gives dust-collector outlet draft and serves as induced-draft-fan indicator. (5) Pressure measurement at this point gives air-heater inlet pressure and serves as forced-draft-fan indicator. (6) Pressure measurement at this point gives air-heater outlet pressure and windbox pressure. (*Energy*, August, 1946.)

The **location** of the pressure connection is dependent upon what pressures are desired. Generally the furnace and breeching draft is required as indicated in Fig. 26-8. Where the unit is more complex, additional pressure connections can be made as shown in Fig. 26-9.

**Instruments.** Where the pressure is over an inch or two of water, a U-tube manometer can be made by heating and bending a piece of glass tubing into the shape of a

U. When filled with distilled water, the total deflection is read directly in inches of water.

Where the pressure is under an inch or two of water, some form of **inclined manometer** (Fig. 26-10) can be used. These are generally filled with a colored oil and are usually calibrated to read directly in inches of water. Before using, they must be carefully leveled by means of the bubble level incorporated in the body; also the zero can be set by means of the sliding scale.

The manometers mentioned are more suitable for temporary work such as a test on a unit that ordinarily does not require a draft indication. Generally, however, a

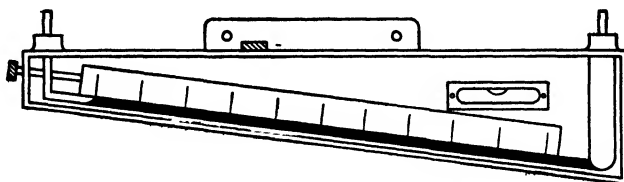


FIG. 26-10. Inclined manometer.

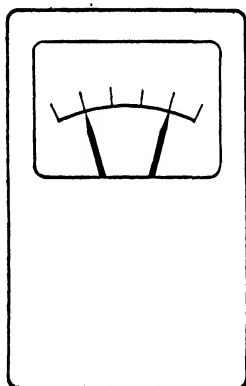


FIG. 26-11. Dual-indicator dial-type draft gauge.

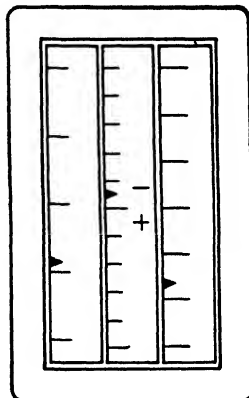


FIG. 26-12. Narrow-face multiple-type draft gauge.

continuous draft reading is necessary, and a permanent draft indicator will be used. These are some form of pressure-sensitive element that is hooked through a linkage to an indicating arm. Some types have two arms on a single dial so that two draft readings can be read simultaneously. Others are arranged with long narrow faces so that as many draft gauges as desired can be set side by side in a panel board with minimum space required (see Figs. 26-11 and 26-12).

### ERRORS IN COAL ANALYSIS DUE TO VARIATIONS IN COMPOSITION

**Uniformity of Composition of Coal.** Coal is a heterogeneous material, a mixture of pure coal and various mineral impurities. Some of these impurities are intimately associated with the coal, and some of them are free impurities which become mixed with the coal in the process of mining. The free impurities are seldom distributed uniformly throughout any particular lot of coal. In sampling and testing, it is thus inevitable that there will be variations in the results, over and above the care in sampling and analyzing. Studies show that each coal has a characteristic deviation

from its own average which is determined by its physical properties and by the conditions of its production and preparation. These factors are:

1. Percentage of ash in the coal
2. Size
3. Ratio of free impurities to total impurities
4. Nature of the free impurities
5. Methods of mining, loading, and preparation
6. Shipment from two or more mines as a single product

There seems to be a normal relationship between the percentage of ash and the deviations from the average of any particular coal which applies to any of the small-sized steaming coals. This is shown for anthracite and bituminous coals in Fig.

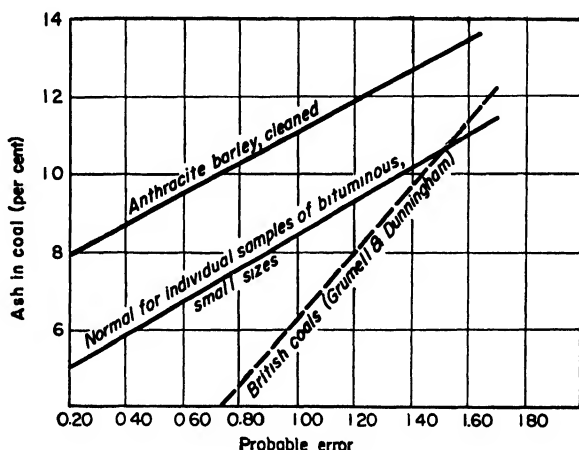


FIG. 26-13. Relation of probable error of individual samples to per cent ash. (Gould, G. B., in *Symposium on Significance of Tests of Coal*, ASTM, Proc., Vol. 37, Part II, p. 355.

26-13. The probable error in this chart refers to the deviation from the average of each coal, above and below which an equal number of tests may be expected to fall.

In using Fig. 26-13 to estimate the probable error of ash analyses, it is important to note that the deviation of individual samples from the average as represented by the curves can be much greater than those shown. The distribution of the deviations from the average in terms of multiples of the probable error  $r$  for the 640 samples of bituminous coal used in the construction of Fig. 26-13 is as shown in Table 26-3.

Table 26-3. Deviations of Individual Samples of Coal from the Average as Shown in Terms of Multiples of Probable Error ( $r$ )

	Per Cent of Actual Tests
Less than $1r$ .....	50.9
Less than $2r$ .....	84.8
Less than $3r$ ..	96.3
Less than $4r$ ..	98.6
Less than $5r$ .....	99.8
Less than $6r$ .....	100.0

Thus, if an 8 per cent ash coal has an error of 0.50 per cent of ash, one-half (50.9 per cent) of all tests may be expected to fall between 7.5 and 8.5 per cent ash ( $8 \text{ per cent} \pm 1 \times 0.50$ ), about 85 (84.8) per cent of all tests may be expected to fall between 7.0 and 9.0 per cent ash ( $8 \text{ per cent} \pm 2 \times 0.50$ ), etc.

In theory, the probable error varies inversely as the square root of the number of tests averaged. Therefore, if tests of five samples of a coal which has a probable error for individual samples of 0.50 per cent are averaged, the group average may be expected to have a probable error of  $0.50/\sqrt{5}$ , or 0.22; and, by the same calculations, 10 tests may be expected to have a probable error of 0.16. In practice, this theoretical gain in accuracy is not achieved in more than half the cases. The gain in accuracy is, nevertheless, very substantial.

Gould offers the following as a rough guide to the desirable minimum number of samples of small-sized bituminous coal, where the probable error is not known:

- Coals under 8 per cent ash = average of not less than 5 samples
- Coals of 8 to 10 per cent ash = average of not less than 10 samples
- Coals over 10 per cent ash = average of not less than 20 samples

In cases where the results are important and yet it is impossible or impractical to secure more than one sample, great care should be exercised in the sampling, and even then the chances of error should be recognized.

**British bituminous coals** are reported to contain a larger proportion of the ash in the form of free impurities, which would account for the somewhat larger deviation which they find for the lower ash coals.

**Possible Reduction of Error by Greater Care in Sampling.** Gould expresses the opinion that, for the great majority of bituminous coals, having no more than 8 per cent ash in the slack and nut sizes, no significant reduction in the probable error can be obtained by any sampling method which could be economically practical in the typical steam plant.

While gross violation of the elementary principles of sampling will undoubtedly increase the magnitude of the deviations from the average, the price of reducing them below that encountered in reasonably careful industrial practice today would probably be higher than is practical.

Extra care in sampling should be taken for high-ash coals, and for the larger screened sizes (egg, stove, or nut), especially in the reduction of the size of the coal as the size of the sample is reduced.

Variations among laboratory tests of the same coal should not be assumed indiscriminately to result from errors of sampling and testing. **Coal is a variable product** and should be regarded as such in any interpretations of testing results.

## BOILER TEST CODES

**ASME Boiler Test Codes.** In making tests of a boiler, it is recommended that a copy of the code for Stationary Steam-generating Units<sup>1</sup> be carefully studied before the test and be available for reference. The purpose of this code is to establish rules for conducting tests to determine:

1. Capacity
2. Efficiency
3. Superheater characteristics
4. Any other operating characteristic

For exact testing, or for making tests for the fulfillment of contracts, this code should be followed. Also, included in this code is a simpler convenient "Short Form," which is tabulation of the data and results (as well as methods of calculation) for a boiler test (see pages 896 to 898). Tablets containing the short form are available at the ASME for a nominal fee.

<sup>1</sup> Stationary Steam-generating units, ASME, New York, 1946.

### SHORT FORM—ASME TEST REPORT DATA AND RESULTS OF BOILER TEST

Test No.	Boiler No.	Location	Date
Owner of Plant			
Test Conducted by	Objective of Test	Rated Capacity	Duration
Boiler Make & Type	Water Walls		Economizer
Heating Surface			
Sq Ft			
Boiler Superheater, Sq Ft	Air Heater		Furnace Volume, Cu Ft
Stoker, Type & Size		Grate Area, Sq Ft	
Pulverizer, Type & Size		Burner, Type & Size	
Fuel Used	Mine	County	State
			Size as Fired

#### Pressures & Temperatures

Item	Description	Units	Data
1	Steam pressure in boiler drum	Psia	
2	Steam pressure in superheater outlet	Psia	
3	Steam temp at _____	Deg F	
4	Water temp entering (economizer) (boiler)	Deg F	
5	Steam quality, per cent moisture or ppm		
6	Air temp around boiler (ambient)	Deg F	
7	Temp air for combustion (combustion air intake)	Deg F	
8	Temp fuel	Deg F	
9	Gas temp leaving (boiler) (economizer) (air heater)	Deg F	
10	Air temp leaving air heater	Deg F	
11	Draft in furnace	In. water	
12	Draft at outlet (boiler) (economizer) (air heater)	In. water	

#### Unit Quantities

13	Enthalpy of saturated liquid (total heat)	Btu/lb	
14	Enthalpy of (saturated) (superheated) steam	Btu/lb	
15	Enthalpy of feed to (boiler) (economizer)	Btu/lb	
16	Heat absorption/lb steam (item 14 - item 15)	Btu/lb	
17	Dry refuse (ash pit + fly ash)* per lb as-fired fuel	Lb/lb	
	If impractical to weigh refuse, this item can be estimated as follows:		
	Dry refuse/lb as-fired fuel		
	$= \frac{\% \text{ ash in as-fired coal}}{100 - \text{per cent combustion in refuse sample}}$	Lb/lb	
18	Btu/lb in refuse (weighted avg)	Btu/lb	

#### Hourly Quantities

19	Actual water evaporated <sup>b</sup>	Lb/hr	
20	Rate of fuel fired (as-fired weight)	Lb/hr	
21	Total heat input $\frac{(\text{item 20} \times \text{item 32})}{1,000}$	kB/hr	
22	Total heat output $\frac{(\text{item 19} \times \text{item 16})^c}{1,000}$	kB/hr	

**SHORT FORM—ASME TEST REPORT. (Continued)****Flue-gas Analysis (Boiler) (Economizer) (Air Heater) Outlet**

Item	Description	Units	Data
23	CO <sub>2</sub>	Per cent by volume	
24	O <sub>2</sub>	Per cent by volume	
25	CO	Per cent by volume	
26	N <sub>2</sub> (by difference)	Per cent by volume	
27	Excess air $\frac{(\text{item 68} - \text{item 67})}{\text{item 67}} \times 100$	Per cent	

**Fuel Data**

Item	Coal as fired, proximate analysis	Per cent weight
28	Moisture	
29	Volatile matter	
30	Fixed carbon	
31	Ash	
	Total	
32	Btu/lb as fired	
33	Ash-softening temp, ASTM method, deg F	
Item	Coal or oil as fired, ultimate analysis	Per cent weight
34	Carbon	
35	Hydrogen	
36	Oxygen	
37	Nitrogen	
38	Sulphur	
31	Ash	
28	Moisture	
	Total	
Item	Coal pulverization	Per cent weight
39	Grindability	
40	Fineness, per cent through 50 mesh	
41	Fineness, per cent through 200 mesh	
Item	Oil	Per cent weight
42	Flash point, deg F	
43	Sp gr, deg API	
44	Viscosity at burner, Saybolt Universal Saybolt Furol	
35	Total hydrogen per cent weight	
32	Btu/lb	

## SHORT FORM—ASME TEST REPORT. (Continued)

## Fuel Data. (Continued)

Item	Gas	Per cent Volume
45	CO	
46	CH <sub>4</sub> methane	
47	C <sub>2</sub> H <sub>2</sub> acetylene	
48	C <sub>2</sub> H <sub>4</sub> ethylene	
49	C <sub>3</sub> H <sub>8</sub> ethane	
50	H <sub>2</sub> S hydrogen sulphide	
51	CO <sub>2</sub> carbon dioxide	
52	H <sub>2</sub> hydrogen	
	Total	
35	Total hydrogen per cent weight	
53	Density (68°F, atmospheric pressure)	
54	Btu/cu ft	
32	Btu/lb	

## Efficiency

55	Efficiency of unit, per cent = $\frac{\text{item 22} \times 100}{\text{item 21}}$	
----	---	--

## Heat Balance

Item		Btu/lb as-fired fuel	Per cent as-fired fuel, Btu
56	Heat absorbed by unit (item 55 × item 32)		Item 55
57	Heat loss to dry gas		
58	Heat loss due to moisture in fuel		
59	Heat loss due to water from combustion of H <sub>2</sub>		
60	Heat loss due to carbon monoxide		
61	Heat loss due to combustible in refuse		
62	Heat loss due to radiation		
63	Unaccounted for (by difference)		
	Total	Item 32	100

Calculations<sup>d</sup>

Item	Description	Unit	Data
64	Heat output in boiler blowdown <sup>c</sup> (to be added to item 22)	kB/hr	
65	Carbon burned/lb of as-fired fuel <sup>f</sup>	Lb/lb	
66	Dry gas/lb as-fired fuel fired <sup>g</sup>	Lb/lb	
67	Theoretical air/lb as-fired fuel burned <sup>h</sup>	Lb/lb	
68	Dry air/lb as-fired fuel burned <sup>i</sup>	Lb/lb	

<sup>a</sup> If fue dust and ashpit refuse differ materially in combustible content, they should be estimated separately.

<sup>b</sup> When direct measurement of heat input or output cannot be made (items 19 or 20 unavailable), the efficiency can be determined by calculating the losses and subtracting from 100. See Chap. 12, p. 384.

<sup>c</sup> Add Btu in blowdown water (item 64).

<sup>d</sup> For the calculation of heat balance, refer to Chap. 12.

$$e = \text{lb water blowdown/hr} \times \frac{(\text{item 13} - \text{item 15})}{1,000}$$

$$f = \frac{\text{item 34}}{100} - \frac{(\text{item 17} \times \text{item 18})}{14,600}$$

$$g = \frac{11 \times (\text{item 23}) + 8 \times (\text{item 24}) + 7 \times (\text{item 26} + \text{item 25})}{3 \times (\text{item 23} + \text{item 25})}$$

$$h = 11.53 \times (\text{item 65}) + 34.36 \left( \frac{\text{item 35}}{100} - \frac{\text{item 36}}{800} \right) + 4.32 \times \frac{(\text{item 38})}{100} \times \left( \frac{\text{item 65} + \frac{\text{item 38}}{267}}{267} \right) + \frac{\text{item 38}}{160}$$

$$i = \text{item 66} + 8 \left[ \frac{(\text{item 35})}{100} - \frac{(\text{item 36})}{800} \right] - \text{item 65} - \frac{\text{item 38}}{100} - \frac{\text{item 37}}{10}$$

**Steel Boiler Institute.** The rating Code<sup>1</sup> contains instructions for making tests on steel boilers, illustrative figures for the location and construction of instruments, log sheets, and calculation sheets.

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